THE STRENGTH

OF

MATERIALS.

BY

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PREFACE.

The essay contained in the following pages was originally printed in the form of a series of articles in *Van Nostrand's Engineering Magazine*, Vol. 20.

The author has made the subject of the articles a "hobby" during the past four years, and has become profoundly impressed with the lamentable want of information, especially among manufacturers and users of materials of construction, concerning the proper methods of testing; and also with the lack of a standard method among professional engineers. It is in the hope of more widely diffusing correct information, and generally popularizing the subject of strength of materials that the articles have been written. Theoretical discussions have been avoided, and it has been endeavored to make them at once elementary and practical.

THE STRENGTH OF MATERIALS.

INTRODUCTION.

The literature upon the subject of Strength of Materials is very extensive. Every professional engineer has, or should have, access to a library of volumes containing records of experiments made for more than a century past, upon every known material of construction, together with mathematical and logical discussions of various theories of strength and resistance, sufficient to enable him to design and proportion structures with that rough approximation to accuracy and economy of material which is at present allowed in most branches of engineering.

In some departments of engineering construction, notably in our American bridge building, the greatest care is taken to thoroughly understand and

apply the principles of strength of materials, and to use materials of known quality; so that in both the theory and the practice of bridge construction, the engineers in charge have gone even beyond the books, and have done better work than any that the books have yet recorded.

In the large majority of constructions, however, this care is not taken. In many cases engineers are not employed at all in designing structures, and, in a certain degree, every man is his own engineer. This is especially true in the construction of ordinary buildings. The results are, in most instances, a reckless waste of constructive material, and frequently, a want of correct proportioning; heavy pieces being placed where light ones should be, and *vice versa.* The waste of constructive materials annually in this country might be figured in millions of dollars. On the other hand, the cost of saving material where it should not have been saved has too often been the sacrifice of human life.

It is chiefly for the benefit of those users of materials of construction who are disposed to be their own engineers that this series of articles is written, but it is hoped that they will not on that account be without interest to members of the engineering profession.

It is intended to present some facts and figures which will show that because a metal is called by the name "iron" it does not therefore necessarily possess a definite strength, but that its strength should first be determined by test; that published records of tests are not always to be relied upon; that many tests themselves are not reliable; and that in using any material in construction not only its strength but its other properties should be considered.

The articles will consist principally of compilations from various authorities, American and foreign, to whom credit will be given as far as possible; but many facts and figures will be given obtained from the writer's own experiments, and from those of his friends,

which have not heretofore been published.

THE STRENGTH OF MATERIALS.

The term "strength of materials," in its widest sense, as used by many authorities, does not include merely what is known as the absolute or ultimate strength—or the resistance, expressed in pounds per square inch or other unit, to final rupture—but also the resistance within certain limits of distortion short of final rupture, as the elastic limit and the point of permanent set; the safe load; the resistance to steady and to suddenly applied loads; and the resistance to repetitions of loads and to shocks and vibrations. It also includes the amount of distortion of the material before final rupture, or within any limit short of final rupture, commonly called ductility; and the property of returning towards its original form after temporary distortion, or elasticity.

DEFINITION OF TERMS.

The external forces applied to materi-

als tending to cause their rupture or alteration of form are called *stresses.*

They are of different kinds, viz. tensile, compressive, transverse, torsional and shearing stresses.

A *tensile stress*, or *pull*, is a force tend ing to elongate a piece. A *compressive stress*, or *push*, is a force tending to shorten it. A *transverse stress* tends to bend it. A *torsional stress* tends to twist it. A *shearing stress* tends to force one part of it to slide over the adjacent part.

Tensile, compressive and shearing stresses are called simple stresses. Transverse stress is compounded of tensile and compressive stresses, and torsional of tensile and shearing stresses.

To these five varieties of stresses might be added *tearing stress*, which is either tensile or shearing, but in which the resistance of different portions of the material are brought into play in detail, or one after the other, instead of simultaneously, as in the simple stresses.

TENSILE STRESS.

Testing Machines.—The resistance of

materials to tensile stress is the one which receives most attention, as it is called into play more frequently than any other, except compressive, and is considered to be in some measure an index of all the other resistances. It is usually determined by means of an apparatus known as a testing machine. The character of this machine may vary with the nature and strength of the pieces to be tested. To test the tensile strength of a piece of twine, for instance, a convenient apparatus would be a spring balance, the twine being fastened at one end to a firm support, and at the other to the hook of the balance. It might also be tested by fastening one end to a firm overhead support, and attaching to the other end such a vessel as a tin pail, in which shot or sand could be poured till the twine breaks, and then weighing the pail and its contents. For testing large sections of metal, requiring many tons to break them, the testing apparatus may be a machine of great size and strength, requiring a high degree of skill both in its construction and in its manipulation.

Such machines have been built in this country in considerable numbers. One of the best known was built several years ago by the late Major Wade, for the United States Government. It is described in his Reports of Experiments on Metals for Cannon (Phila., 1856.) Copies of this machine, as improved subsequently by Capt. Rodman, are now in use at the Washington Navy Yard and in the U. S. Army Building in New York. One of these machines has been used for several years in the Woolwich Arsenal, in England.

Fairbanks and Co., the well known scale makers, of St. Johnsbury, Vt., and more recently Riehle Brothers, of Philadelphia, have paid considerable attention to the building of testing machines, and machines of their makes are to be found in various iron-making and manufacturing establishments throughout the country. All of these machines weigh the amount of applied stress by means of a combination of levers and scale beams. In the Riehle machine the stress is applied by

means of a hydraulic press. In the Wade and the Fairbanks machines the stress is applied through screws, levers and wheel gearing, or some combination of them, the particular combination varying in different machines.

For testing very large specimens, requiring hundreds of tons to break them, hydraulic presses have been used, in which the stress is registered by gauges showing the pressure of the liquid used in the press. Such a machine is in use at the works of the Keystone Bridge Co. in Pittsburgh. A machine has recently been built by Albert H. Emery of Chicopee, Mass., for the use of the United States Board appointed to test Iron, Steel, etc., but it has not yet been erected in position for use on account of the neglect of Congress to make an appropriation for the continuance of the work of the Board. It is designed for a capacity of 800,000 pounds, and is believed by engineers who have inspected it to be the most accurate machine of large capacity ever made.

John L. Gill, Jr., of Pittsburgh, has recently built a testing machine of 100,000 pounds capacity, for general work, which, as he claims, remedies some of the defects possessed by all machines of this class heretofore built.

It is frequently supposed that to obtain the tensile strength of a piece of iron, or other material, any testing machine will answer, no matter how roughly built or how badly used, that the specimen may be of any convenient size and shape, and that any person of ordinary intelligence is capable of making an accurate test. A review of what has been written by various "authorities" will convince any one how erroneous is this idea.

Mr. Kirkaldy, of London, the eminent experimenter, who has written several works containing his observations, quotes Mr. S. Hughes as saying that writers on the strength of materials in the last century seldom assigned a less tensile strength than thirty tons (of 2,240 lbs.) as the weight which would tear asunder a bar of ordinary wrought iron one inch

square. Thus Emerson quotes the tensile strength of bar iron at 34 tons; Telford, 29.29 tons; Drewry, 27 tons; while at the present day Templeton gives 25 tons; Beardmore, 26.8 tons; Brown, 25 tons; and Hodgkinson, probably from more careful experiments than any other, 23.817 tons. In reference to these figures Mr. Kirkaldy states that he does not think that there is any satisfactory evidence in the experiments adduced to show that the iron now produced is inferior to that made during the last century. The difference is rather due to experiments having been performed by so many persons, whilst the pieces tested by each were so few—to the different kinds of apparatus employed—to the results having been more carefully recorded by some than by others—to the extreme meagerness of details, and to the complete want, with a few exceptions, of the makers' names or brands—which renderered futile any attempt at comparison. The various means employed to tear the piece asunder were—applying weights

directly to the specimen, single lever and weights, compound lever and weights, combined with a hydraulic press, hydraulic press alone, with either a loaded valve or a gauge to indicate the pressure.

When such wide variations are found in the figures of the strength of bar iron published by those who are supposed to be authorities on the subject, and from whom accurate statements ought to be expected, is it any wonder that figures reported by manufacturers should vary still more, when their tests are frequently made on inaccurate machines, by unskilled operators, and when the results are apt to be influenced by incorrect and irregular methods of test, and by variety of shapes and methods of preparing test specimens, as well as by self interest?

A striking example of the difference in the apparent strength of wrought iron as obtained from different testing machines is given in a paper in the *Metallurgical Review* for September, 1877, by Mr. John I. Williams. In testing the

iron for the Point Bridge, Pittsburgh, three machines were used. One is said to have given the tensile strength from three thousand to five thousand pounds per square inch below what it should indicate, and to have "pulled crooked," causing flat specimens to tear at one edge before the iron was strained to the greatest load it would carry. The second machine was supposed to be "nearly correct." The third machine was found on making comparative tests to indicate, on an average, 10,000 pounds higher than the first, "thus proving conclusively that the ultimate strength of iron depends on where the testing is done, and what kind of a machine is used."

Shape of Specimen.—The shape of test specimen has sometimes an important influence upon the record of strength. It is very common to shape test pieces as shown in Fig. 1, in which A represents a piece of plate or flat bar, and B a piece of round iron or other material. In testing pieces of this shape, especially in wrought iron, brass, or other ductile material, the

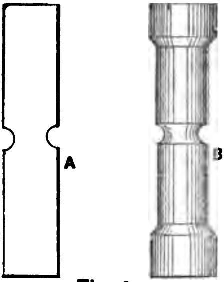


Fig. 1

result will almost invariably be higher than the true result as determined by test pieces of the shape shown in Fig. 2. The following facts may be given in confirmation of this statement.

Mr. D. K. Clark, in his "Rules, Tables and Data for Mechanical Engineers,"* notes a test made by T. E. Vickers, of a piece of steel turned down to one inch in diameter and fourteen inches in length, which gave a tensile strength of sixty tons per square inch, while a bar of the same steel turned down to $\frac{3}{4}$ inch in a circular notch in the middle, broke at $79\frac{1}{2}$ tons per square inch.

* Published by D. Van Nostrand, New York.

C. B. Richards, C.E., in the Transactions of the American Society of Civil Engineers, Vol. II, p. 339, gives the following results of tests of different-shaped specimens of the same material: For "Burden's best" bar iron the "short" specimens, (shaped as in Fig. 1), gave 62,000 pounds as the average value for the tensile strength per square inch of original cross section of the finished specimen, while the "long" specimens (shaped as in Fig. 2), gave only 49,600

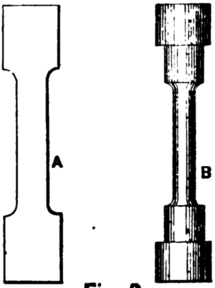


Fig. 2

pounds for that value, the difference in results corresponding to 25 per cent. of the smaller value. For "Bay State"

boiler plate, the short specimens gave 52,100 pounds, and the long 47,450 pounds, the variation being 10 per cent. There was a great difference in the ductility of these irons, the Burden bar (long specimens) stretching on an average 30.1 per cent. before breaking, and the Bay State plate only 12.4 per cent., the length of the portion on which the stretch was measured being five inches in each case.

Col. Wilmot found, using proof bars of a form similar to Fig. 3, as a result of

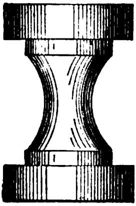


Fig. 3

eight trials of Bessemer steel, a mean of 153,677 pounds per square inch, and on the same steel turned to a cylindrical form three inches long and one square

inch in cross section, the mean was only 114,460 pounds per square inch. (Levi and Kunzel's Report on Phosphor-Bronze).

Kirkaldy made some experiments to show the variations in results for tensile strength of Fagersta steel plates, arising from differences in the form and proportions of the specimens. One set was ten inches long and ten inches wide at the parallel middle portion, the second was $1\frac{1}{2}$ inches wide and $4\frac{1}{2}$ inches long, and the third was $2\frac{1}{4}$ inches wide and 100 inches long. The results were as follows (Clark's Rules, Tables and Data):

UNANNEALED.

	Elastic tensile strength tons per sq. in.	Breaking weight tons per sq. in.	Ratio of elastic strength to breaking weight per cent.	Permanent extension per cent.	Area of fractured section per cent. of original.
Length=breadth	16.05	26.39	60.0	29.7	48.8
Length=3 breadths..	15.56	25.56	60.3	35.0	43.2
Length=44 breadths.	13.71	23.00	59.2	14.0	43.1
ANNEALED.					
Length=breadth	13.53	23.65	57.0	33.1	39.1
Length=3 breadths..	12.98	23.16	56.0	39.3	36.5
Length=44 breadths.	12.04	21.31	56.5	16.5	34.4

Kirkaldy found that the influence of the shape of the specimens upon the results varied with the softness or ductility of the materials, and that this influence was important in the case of soft or ductile materials, but became hardly appreciable with hard and brittle materials.

Richards found that the breaking weight per square inch of *fractured area* give nearly equal values with either shape. In the case of the "short" specimen the shape tends to prevent any contraction of cross section, and this would tend to make the apparent strength per square inch of fractured section approximate to that of a long piece which contracted to a greater degree.

The writer recently made some tests to determine the influence of shape of specimen upon some samples of charcoal-refined iron furnished by one of the mills in Pittsburgh which has a wide reputation for the superior quality of its product. The following table shows the results:

	Breaking Strength.		Elongation per cent.	Increased strength of short specimen per cent.
	Per square inch of original section.	Per square inch of fractured section.		
	lbs.	lbs.		
No. 1.	52,261	97,567	16.	—
No. 2.	54,439	71,668	—	4.2
No. 3.	59,682	76,531	15.	—
No. 4.	63,268	75,601	—	6.0

No. 1 was a piece of flat bar, $2'' \times \frac{1}{2}''$, a "long" specimen, shaped as in Fig. 2 A, the distance between the shoulders being 5 inches and the original section of the portion stretched being $1'' \times \frac{1}{2}''$. No. 2 was a "short" specimen for the same bar, shaped as in Fig. 1 A, the minimum section being the same as No. 1, $1'' \times \frac{1}{2}''$.

No. 3 and No. 4 were a "long" and a "short" specimen from a piece of "C.H. No. 1" boiler plate $\frac{3}{8}$ inch thick, stamped "60,000 lbs.," shaped as in Fig. 2 and Fig. 1 respectively. All the tests were made in the direction of the fiber,

all were made on the same testing machine, the same care was taken in fitting, and the same length of time taken in each test, so as to secure as far as possible a uniform set of conditions in each. It will be seen that the short specimen in both cases gave the highest results, although the variation is not so great as that given in the experiments of Richards. The strength per square inch of fractured section of No. 1 is unusually high, and much higher than that of No. 2, the short specimen of the same material. This does not accord with Richards' statement, given above, that the breaking weights per square inch of fractured area give nearly equal values with either shape. The strength per square inch of fractured section of No. 3 and No. 4, however, agree quite closely.

Commander L. A. Beardslee, U. S. N. has recently made a large number of such comparative tests, which confirm the general fact that the short specimens give the highest apparent strength; but the results have not yet been published.

The above results of experiments should be sufficient to show that tests of "short" specimens of ductile materials are of little or no value for giving their actual strength as used in construction. It is a well known fact, however, that in this city and elsewhere, tests are made of short specimens of soft and ductile irons, and the figures obtained published as the "strength" of the materials, when their actual strength as used in a structure is much lower. Such published figures are not only unreliable but unfair. The following reasons may be given why the use of short specimens should be abandoned in tests for commercial purposes.

1. In testing short specimens no accurate measurement can be made of their extension before rupture, as a means of comparison of ductility, a quality, the knowledge of which is quite as important as that of absolute strength.

2. In testing short specimens, two specimens of different materials may give the same results, while long specimens of these materials may give different results.

Thus, two short specimens may each show a tensile strength of 60,000 pounds, while if the specimens were of the long shape, one might show 50,000 and the other 55,000 pounds, if one were more ductile than the other. The short specimens, therefore, fail to give not only correct absolute results, but also relative results.

3. There is no *standard* shape of short specimens, and as the difference in results due to various shapes of short specimens is unknown, no proper comparison can be made of the results of different experiments on such specimens.

4. As shown by the experiments given above, there is no standard relation between the strength of a short specimen and that of a long specimen; hence, if a test is made of a short specimen, it furnishes no means of knowing what strain the material will bear in actual service.

5. As it is always desirable before using any material of construction to know its strength under the most unfavorable conditions, or to know its least,

rather than its greatest, strength under any conditions, the test of a sample of the material should show its least strength, and not its greatest, as does the short specimen. Of what advantage would it be to know that a short specimen taken from a bridge-rod will show 50,000 pounds strength, when if a long piece, or the whole rod were tested it would show only 40,000 pounds?

Other Incorrect Tests.—As too high an apparent strength may be obtained in testing specimens of a certain shape, so a specimen of another incorrect shape, or one of a correct shape incorrectly placed in the testing machine, may give too low a result. This occurs when, on account either of the shape of the specimen or of the manner in which it is placed in the testing machine, the line of strain of the machine does not coincide with the axis or central line of the piece tested.

In Fig. 4, A is a piece that is incorrectly shaped, the axis of the heads not being in a line with the axis of the middle portion. If placed in the testing machine

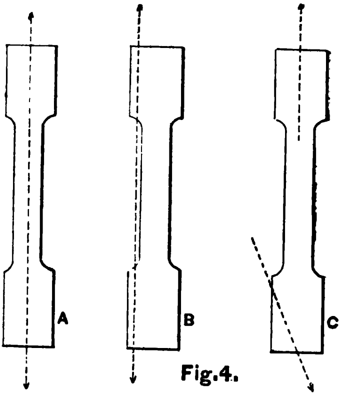


Fig. 4.

in the manner that is ordinarily correct, viz.: with the axis of the heads in the line of strain, as shown by the arrows, the test will be an incorrect one and the result will be too low. The piece will break partly by *tearing*; it will *bend* as soon as the strain is applied, and the fibers will give way on one side before the other. B represents a correctly-shaped specimen, but being incorrectly placed in the testing machine, so that the line of strain is not through the axis of the specimen, as indicated by the arrows,

it will also break partly by tearing and give too low a result. C is a correctly-shaped specimen, but the upper end is rigidly held in the clamps of the testing machine in the correct position, while from an inaccuracy of adjustment of the lower clamp, or of the testing machine itself, the lower end is pulled sidewise, causing a tearing strain. In all these cases the tendency is to bend the specimen before breaking it. The writer has sometimes seen tests made in which the specimen was so much bent before it was broken that the bend could be detected by the eye, and plainly shown on placing a short straight edge against the side of the specimen. More frequently he has seen tests in which the bend was imperceptible to the eye, but could be detected by an apparatus used for the purpose (which will be hereafter described) which magnified the visible appearance of bending. In many cases, by a slight re-adjustment of the clamps which held the specimen, the bend could be made to take place first on one side of the speci-

men and then on the other. It may be imagined how valueless the result of a test of cast iron, or of any brittle material would be in which the breaking was caused partly by pulling and partly by bending.

Mr. Hodgkinson states that the strength of a rectangular piece of cast iron drawn along its side is about one-third, or a little more, of its strength, to resist a central strain. It is evident that this ratio (one-third) would be given only by a few certain shapes pulled in a certain manner, and that it would vary with every shape and with every variation of the error of the test. The resistance of any material to tearing bears no relation whatever to its resistance to direct pull, as may be conclusively proven by the simple experiments of pulling and tearing a slip of paper or of tin-foil.

A gentleman in this city states that in making a great number of tests of special grades of cast iron, which have been frequently found by other experimenters to have a strength of about 30,000 pounds

per square inch, he has not been able to find a piece having a strength much over 20,000 pounds. The discrepancy is so large that it can scarcely be accounted for but by supposing that one of the testing machines is not correctly adjusted, or that in the second case the specimens are not correctly placed in the clamps

The error which may arise in a test of this kind is usually much greater with cast iron or other brittle material than with a ductile material like wrought iron The ductility of the latter allows it to be partially "drawn into a line," while the former will often break before the drawing into line can take place.

Influence of Time upon Tests.—A difference in results may be obtained in testing two specimens of the same material, if the *time* occupied in one test is longer than that occupied in the other. This difference due to time is in some cases inappreciable, perhaps too small to be measured; but in other cases it is enormous. *With wrought iron and soft rolled steel, the more gradual the test the*

higher will be the result. With tin, zinc and some other metals and some alloys, the more gradual the test, the lower the result. These statements are not yet generally believed among unscientific men, probably because it has only been within the last few years that the facts have been brought into prominent notice by experimenters. For abundant confirmation of them, reference may be made to several papers by Prof. R. H. Thurston, published in the Transactions of the American Society of Civil Engineers, in the years 1874, 1875 and 1876. He divides the metals into two classes.

1. "Metals subject to internal strain by artificial manipulation, and which may exhibit an elevation of the elastic limit by strain, and *decreased power of resisting stress under increased rapidity of distortion.* The ordinary irons of commerce are typical of this class."

2. "Metals of an inelastic viscous character, not subject to internal strain, and not usually exhibiting an elevation of the elastic limit by strain, and which offer

increased resistance when the rapidity of distortion is increased. Tin is a typical example of this class."

Among a great number of experiments by Prof. Thurston—in which the writer had the honor to be associated as assistant—upon the influence of time upon resistance, the following may be mention ed in confirmation of the above statements.

1. Two pieces of ordinary merchant iron, one inch square, taken from the same bar, were tested by bending stress. They were placed on supports twenty two inches apart, and the pressure applied by a screw and registered by a platform scale. One was tested as rapidly as possible, the pressure and deflection being read and recorded at every 20 or 40 pounds, about one hour being occupied in the whole test. A deflection of $5\frac{1}{2}$ inches was caused by a load of 2350 pounds. The other was tested very slowly, and was "rested," frequently under strain, for intervals of from 12 to 48 hours, the whole test requiring more

than three weeks' time. A load of 2640 pounds caused a deflection of less than three inches.

2. Two pieces of cast tin, from the same bar, were tested by tensile stress. The test of one was made in eight minutes, and the highest resistance was 3,400 pounds per square inch. The test of the other occupied thirty minutes, and the highest resistance was only 2000 pounds per square inch. Tests by tensile, transverse and torsional stress on tin and on zinc, and on the soft white alloys of tin and copper, invariably gave similar results.

In tests of cast iron, hard steel, and brittle materials in general, the effect of time has not been determined, but it is supposed to be very slight.

Directions for Making Tests.—The object of a test of a material of construction is to learn all that should be known concerning the properties it possesses which make it valuable for the purpose for which it is to be used. No engineer should be satisfied to use in an important

structure iron of which he knows only the tensile strength and that inaccurately. He should know its ductility, or amount of extension before breaking, which measures to some extent its resistance to rupture by shock, and its strength within the elastic limit, which measures approximately its resistance to distortion. For many purposes he should know its coefficient of elasticity, or stiffness, its uniformity of strength, and its possession of, or freedom from, internal strain. All of these may be determined by a tensile test properly conducted, with a correct machine, and an accurate apparatus for measuring elongations. A few directions for making such a test may be of service.

In the first place the testing machine itself should be tested, to determine whether its weighing apparatus is accurate, and whether it is so made and adjusted that in the test of a properly made specimen the line of strain of the testing machine is absolutely in line with the axis of the specimen.

Secondly.—The specimen should be so

shaped that it will not give an incorrect record of strength. Under no circumstances should the test of a piece shaped as was shown in Fig. 1 or Fig. 3 ("short" specimen) alone be relied upon to determine strength. The piece should be of uniform minimnm section for several inches of its length. The writer recommends five inches in length between the extreme points between which measurements of extension are made, for the *standard* size of specimen, as being the most convenient length for the testing machines now most in use, for calculation of extension in per cent. of length, and for comparison of results with those of other experimenters. Considerable confusion exists in published records of the per cent. of extension of materials as given by different authorities, because they used different lengths in testing. A ductile material may extend 30 per cent. of its length if the specimen tested is five inches long, but if the piece tested is only 1 inch long it might show an extension of 100 per cent. Prof. Thurston

gives the following formula for total extension

$$\text{Extension} = Al + fd,$$

where l is the length and d the diameter of the piece, A is a constant, and f is a variable function of the diameter. The length of a specimen, as well as the diameter or area of cross section should always be given in the record of a test.

Thirdly—Regard must be had to the time occupied in making tests of certain materials. When wrought iron and soft steel can be made to show a higher apparent strength by keeping them under strain for a great length of time, it is well to test them as rapidly as possible to obtain their minimum strength; and in accepting results of tests of these metals from interested parties, it is well to know what length of time they have taken in testing them. It is fortunate that metals of the tin-class are not used in construction to resist heavy stresses. If they were, no test ought to be considered a reliable one which did not occupy a time

as long as the material was expected to have "life" in actual service, for, as was shown in the case of the test of tin, above mentioned, the material might be nearly twice as strong under a rapid as under a slow test. In recording the tests of all such materials the time occupied in making each test should be given.

Fourthly—Accurate measures should be made of the extension under each successive increment of load in order to determine all the properties of the material, other than its mere absolute tensile strength, which make it valuable in construction.

Methods of Measuring Elongation.—The method of making measurements of elongation will depend upon the degree of accuracy which is desired. Measurements to $\frac{1}{100}$ of an inch may be made by taking distances by a pair of dividers between two fine lines drawn on the specimen, and reading this distance on a fine metal scale. In testing specimens five inches in length between these lines, this degree of accuracy will give approximately

the elastic limit, and the percentage of stretch at different loads beyond the elastic limit, but it will not give the extensions corresponding to loads within the elastic limit, which are a measure of the stiffness, or co-efficient of elasticity, nor the position of the elastic limit with that approach to preciseness which is desirable in competitive tests or in scientific investigations. Reading of extensions to $\frac{1}{1000}$ of an inch may be made by means of two divided plates, clamped one on each end of the specimen and sliding on each other, one carrying a fine scale and the other a vernier; or by means of a micrometer screw, with scale attached, clamped to one end, the point of the screw abutting against a rod clamped to the other end—practically a modification of the micrometer calipers.

For still finer work, readings may be made to $\frac{1}{10,000}$ of an inch with accuracy, by the method first adopted at the testing laboratory of the Stevens Institute of Technology, and now used there to the

exclusion of all other methods. Two very fine micrometer screws are firmly clamped to one end of the test specimen, the ends of these screws abutting against two rods clamped to the other end. The screws have each fifty threads to the inch, and the head is divided into 200 parts.

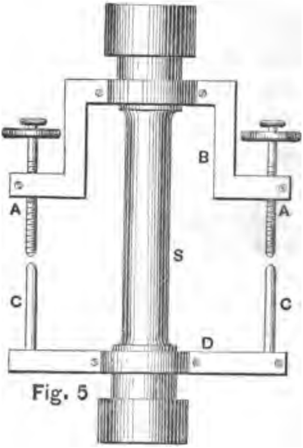


Fig. 5

A sketch of this apparatus is shown above. A clamping piece, B, carries the two screws AA, and another clamping

piece D carries the two rods CC. As the test-specimen S is extended in the testing machine, the points of the screws and rods recede from each other, and the distance each screw requires to be moved forward to make contact at each addition of load is the amount of extension due to such addition. It is impossible to obtain a reading of contact accurate to $\frac{1}{10,000}$ of an inch by the senses of sight or touch, but it is indicated with perfect accuracy by causing the touch of each screw on its opposite rod to close the circuit of a weak electric current and thereby ring a small bell. For this purpose the upper part of the rods CC require to be insulated from the rest of the apparatus. The writer made some experiments to determine the accuracy of the reading by electric contact, and found that there was no error as large as $\frac{1}{40,000}$ of an inch. In taking a reading, the screw A on the right hand is slowly turned till the bell rings, which indicates

that contact has taken place. The reading on the divided head is then recorded; contact is broken with the right hand screw and made in like manner with the left hand screw. The difference between the mean of the two readings and the mean of two previous readings is the amount of change of length of the specimen. Two screws are necessary to eliminate the error which would occur if through any cause the piece bends during the pulling. In ordinary tests, there is, perhaps, not one test in a thousand in which the piece will not bend to some extent, and the bending will be plainly indicated by this instrument, although it would remain undiscovered without it.

It is frequently objected that measuring extensions of test pieces to $\frac{1}{10,000}$ of an inch is an unnecessary refinement; but by such measurements only is it possible to obtain the coefficient of elasticity or the elastic limit on specimens only five inches in length of portion stretched, and in many practical cases, as in bridge

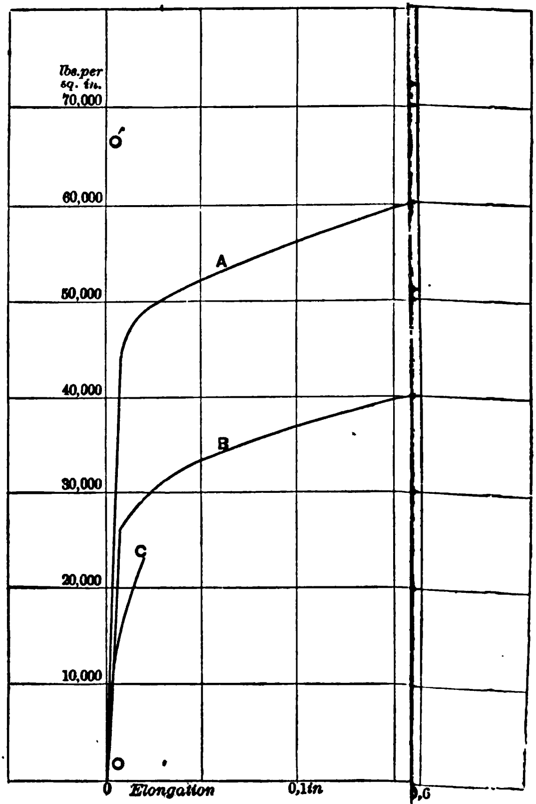
building, a knowledge of these is desirable. By the method of measurement above described, results have been obtained from five inch specimens of cast iron which are fully as accurate as those obtained by Hodgkinson on rods ten feet long, and with very much less trouble and expense. The following is the record of a test recently made by the writer, of a piece of cast iron, turned $1\frac{1}{8}$ inches in diameter and five inches in length between fillets :

RECORD OF TEST OF CAST IRON.

Load.	Extension in five inches.			Co-efficient of elasticity
	Right hand.	Left hand.	Mean.	
lbs. per sq. in.	inch.	inch.	inch.	
500	0.0007	-0.0005	0.0001	25,000,000
1,000	0.0010	-0.0006	0.0002	25,000,000
1,400	0.0012	-0.0005	0.0003	23,333,333
2,000	0.0014	-0.0003	0.0006	16,666,667
2,500	0.0015	0.0000	0 0008	15,625,000
3,000	0.0017	0.0003	0.0010	15,000,000
4,000	0.0026	0.0000	0.0013	15,384,615
5,000	0.0024	0.0011	0.0018	13,888,889
6,000	0.0027	0.0016	0.0022	13,636,364
7,000	0.0032	0.0019	0.0026	13,076,923
8,000	0.0035	0.0028	0.0032	12,500,000
9,000	0.0039	0.0034	0.0037	12,162,162
10,000	0.0044	0.0038	0.0041	12,195,119
11,000	0.0050	0.0044	0.0047	11,702,128
12,000	0.0053	0.0055	0.0054	11,250,000
13,000	0.0057	0.0061	0.0059	11,016,949
14,000	0.0066	0.0066	0.0066	10,606,061
15,000	0.0074	0.0076	0.0075	10,000,000
16,000	0.0083	0.0086	0.0085	9,411,706
17,000	0.0090	0.0093	0.0092	9,239.130
18,000	0.0097	0.0104	0.0101	8,910,891
19,000	0.0108	0 0116	0.0112	8,482,143
20,000	0.0120	0.0130	0.0125	8,000,000
21,000	0.0134	0.0145	0.0140	7,500,000
22,000	0.0152	0.0168	0.0160	6,875,000
23,000	0.0171	0.0197	0.0184	6,140,218
23,285	broke.			

RECORD OF TEST OF CAST IRON.

Load.	Extension in five inches.			Co-efficient of elasticity
	Right hand.	Left hand.	Mean.	
lbs. per sq. in.	inch.	inch.	inch.	
500	0.0007	-0.0005	0.0001	25,000,000
1,000	0.0010	-0.0006	0.0002	25,000,000
1,400	0.0012	-0.0005	0.0003	23,333,333
2,000	0.0014	-0.0003	0.0006	16,666,667
2,500	0.0015	0.0000	0.0008	15,625,000
3,000	0.0017	0.0003	0.0010	15,000,000
4,000	0.0026	0.0000	0.0013	15,384,615
5,000	0.0024	0.0011	0.0018	13,888,889
6,000	0.0027	0.0016	0.0022	13,636,364
7,000	0.0032	0.0019	0.0026	13,076,923
8,000	0.0035	0.0028	0.0032	12,500,000
9,000	0.0039	0.0034	0.0037	12,162,162
10,000	0.0044	0.0038	0.0041	12,195,119
11,000	0.0050	0.0044	0.0047	11,702,128
12,000	0.0053	0.0055	0.0054	11,250,000
13,000	0.0057	0.0061	0.0059	11,016,949
14,000	0.0066	0.0066	0.0066	10,606,061
15,000	0.0074	0.0076	0.0075	10,000,000
16,000	0.0083	0.0086	0.0085	9,411,706
17,000	0.0090	0.0093	0.0092	9,239,130
18,000	0.0097	0.0104	0.0101	8,910,891
19,000	0.0108	0.0116	0.0112	8,482,143
20,000	0.0120	0.0130	0.0125	8,000,000
21,000	0.0134	0.0145	0.0140	7,500,000
22,000	0.0152	0.0168	0.0160	6,875,000
23,000	0.0171	0.0197	0.0184	6,140,218
23,285	broke.			


lbs.per sq. in.
70,000
60,000
50,000
40,000
30,000
20,000
10,000
O'
O
A
B
C
0
Elongation
0,1in

A.
A.B. and C. act

It will be seen that the greatest difference between the readings indicated by the screw on the right hand and those on the left, is only 0.0026 inches. As these screws were over six inches apart, the amount of bending of the specimen to cause this difference must have been almost infinitesimal. The accuracy of the test is further shown by the great regularity of the increase of the mean elongation and of the decrease of the coefficient of elasticity. The total error of any figure in the column of mean extension is not greater than 0.0002 inch.

Graphic Representation of Results.— The plate on the opposite page is a graphic representation of the results of tests of specimens of cast iron, wrought iron and steel. The curves, or *strain diagrams* are made by "plotting" the figures of stress and elongation recorded during the test. The test of cast iron represented in the plate is the same as that recorded in the table above. Each curve is a complete record of all the

properties of the material which can be determined by test. The ordinates, or perpendicular distances of any point of each curve from the base line, represents the applied stress per square inch; and the abscissa, or horizontal distance from the line OO,′ represents the corresponding extension. That point of each curve at which it first bends towards the right hand indicates the elastic limit. The inclination of the initial portion of the curve to the vertical, OO′, measures the stiffness within the elastic limit, or co-efficient of elasticity. This method of representing results is now used by all scientific experimenters on strength of materials.

Elastic Limit and Coefficient of Elasticity.—These terms may here be defined. The elastic limit is that point at which the extensions cease to be proportional to the stresses, and begin to increase in a greater ratio than the extensions. In the diagrams, as stated above, it is the point at which the diagrams begin to curve away from the initial straight line.

It will be seen from the diagrams that wrought iron and steel give a well defined elastic limit, while there is no elastic limit shown in the cast iron test, the elongations varying in a more rapidly ratio than the stresses, from the beginning of the test. The elastic limit is sometimes defined as the point at which the first "permanent set" takes place; the permanent set being the extension which remains after the load causing the extension has been removed. Within the elastic limit, according to this definition, a material that is extended by a load will, when the load is removed, return entirely to its original length; and beyond this limit it will only partly return, the amount of permanent increase of length being the set. This definition is not now considered, by the best authorities, as good as the first, as it is found that with some materials a set occurs with any load, no matter how small, and that with others a set which might be called permanent vanishes with lapse of time, and as it is impossible to get the point of

first set without removing the whole load after each increase of load, which is frequently inconvenient. The elastic limit defined, however, as the point at which the extensions begin to increase at a higher ratio than the applied stresses, usually corresponds very nearly with the point of first measurable permanent set.

The co-efficient (or *modulus*) of elasticity is a term expressing the relation between the amount of extension or compression of a material and the load producing that extension or compression.

It may be defined as the load per unit of section divided by the extension per unit of length; or, the reciprocal of the fraction expressing the elongation in one inch of length, divided by the pounds per square inch of section producing that elongation.

Let P be the applied load, K the sectional area of the piece, L the length of the part extended, l the amount of the extension, and E the coefficient of elasticity. Then

$\frac{P}{K}$ = the load on a unit of section.

$\frac{l}{L}$ = the elongation of a unit of length.

$$E = \frac{P}{K} \div \frac{l}{L} = \frac{PL}{Kl}.$$

The coefficient of elasticity is sometimes defined as the figure expressing the load which would be necessary to elongate a piece of one square inch section to double its original length, provided the piece would not break, and the ratio of extension to the force producing it remained constant. This definition follows from the formula above given, thus: If K = one square inch, L and l each = one inch, then E = P.

In the diagrams the coefficient of elasticity within the elastic limit, is indicated by the inclination of the initial portions of the diagram from the vertical, the diagram whose initial portion deviates least from the vertical having the highest coefficient.

Strength Per Square Inch of Fractured Section.—The strength per square

inch of fractured section, as determined by dividing the recorded breaking weight by the area measured after fracture, is stated by some writers to be a correct measure of the valuable properties of a material; thus of two samples of iron which show the same strength per square inch of original section, the one which shows the greater strength per square inch of fractured section is the more valuable. In many cases an iron which has a very high tensile strength per square inch of original section is an unsafe iron to use in construction, and one which has a much lower strength is safer, if the latter have the higher strength per square inch of fractured section. Kirkaldy states that for comparing the qualities of iron the breaking weight per square inch of the fractured area should be taken, and *not* the breaking weight per square inch of original section.

This method of comparing the qualities of materials, however, is not as good as that of comparing the strength per

square inch of original section *together with the extension before breaking*, and with the uniformity of extension or of reduction of area in different portions of the length of the specimens, for several reasons:

1. The breaking strain per square inch of fractured area in ductile materials is frequently uncertain, as the piece may diminish in section very rapidly in the last few seconds before final rupture, and during those few seconds its resistance decreases rapidly, but apparently gradually, from the maximum recorded resistance of the specimen to perhaps less than half of the maximum. The writer has frequently found that the resistance of a piece recorded an instant before rupture was much less than half the recorded maximum resistance, and so rapidly did this resistance decrease that its final amount could not be measured. In such cases it was impossible to state what really was the resistance per square inch of fractured section. Commander L. A. Beardslee, U. S. N., in his tests at

the Washington Navy Yard has found similar results.

2. In ductile materials the fracture is frequently so much distorted that its area cannot be ascertained with any approach to accuracy.

3. Of two metals of the same class the one which has the greater tensile strength per square inch of fractured section *may not* be the better metal. For instance, of two pieces of a certain class of metal, say, soft steel, iron, or brass, of one square inch original section, suppose one has a breaking weight of 60,000 pounds, and the other of 50,000 pounds. The first elongates 20 per cent. and its fractured area is $\frac{3}{4}$ of a square inch. The second elongates 30 per cent., and has a fractured area of $\frac{1}{2}$ square inch. The first would have a strength per square inch of fractured section of 80,000 pounds, and the second of 100,000 pounds, yet it is easily seen that the first is the better metal. It is also seen by this example that the product of tensile strength per square inch of original

section, multiplied by the extension, is not necessarily a measure of quality; for in the first case the product is 1,200,000 and in the second 1,500,000; yet the first may be superior, since any elongation greater than 20 per cent. is generally valueless.

4. In tests of metals, or of any materials, having no greater ductility than cast iron, the reduction of section is too small to be conveniently measured, while it is quite easy to measure its elongation. The ductility of such materials therefore cannot be compared by measuring their fractured area, while it can be compared by measuring their elongation with proper apparatus.

True Method of Comparing Qualities of Materials.—The only convenient method of comparing with accuracy all the qualities of materials, so far as these qualities can be learned from tensile tests, is that of plotting the results of the tests and comparing the "strain diagrams," or the graphic method as above described. Such a comparison may best

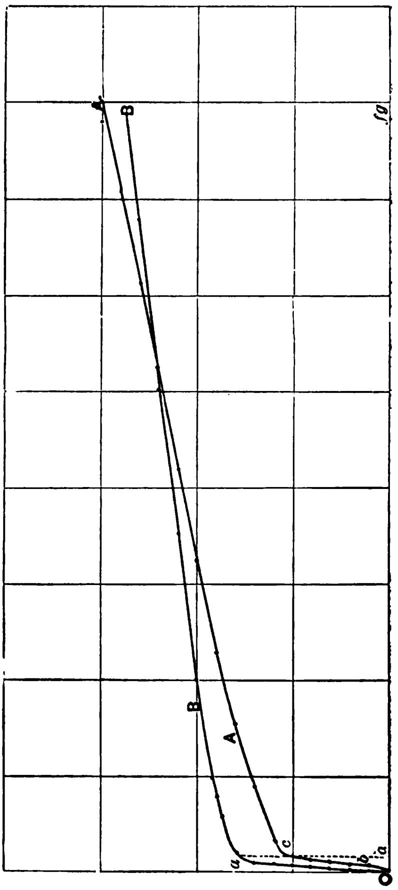
be illustrated by the two ideal strain diagrams in the cut below. The dots repre sent the observations made in each test. The specimens are supposed to be of the same shape and size and to be tested in exactly the same manner.

The following record of the two specimens here represented might be given by the operator of the testing machine:

	A	B
1 Tensile strength per square inch of original section....	60,000	54,000
2 Tensile strength per square inch of fractured section..	90,000	80,000
3 Elongation, per cent.........	25	24
4 Elastic limit, lbs. per sq. inch.	22,000	30,000

In a rough test items 1, 2 and 3 only would be given (by some item 1 only) and from these items any one would suppose that A was much the better material. Item 4, if given, might correct this opinion, but it might only lead to doubt as to the accuracy of the test.

An inspection of the curves, however, shows that B is a much better material than A. 1. In B the initial part of the diagram is a straight line to *a*, showing


A
B
fg
B
A
c
a
b
a
O

perfect homogeneity and freedom from internal strain; in A the initial line has a bend at *b* showing either want of homogeneity or the presence of internal strain. (This may, however, indicate only an inaccuracy in the record of the first part of the test.) 2. The inclination of the initial portion of B is much less than that of A, showing a higher coefficient of elasticity, usually a valuable property in constructive material. 3. The elastic limit of B is much higher than that of A. 4. The area of the triangle $O\,a\,d$, representing the *amount of work* done in extending the piece B within the elastic limit, or its "elastic resilience," is much greater than that of the corresponding triangle $O\,c\,d$ of the piece A. The piece B, therefore, would be capable of enduring a much greater shock without permanent distortion than the piece A. 5. The total area included between the diagram of B and the base line $O\,a\,B\,B\,f$ is greater than the corresponding area $O\,c\,A\,A\,g$ of the piece A, showing that B has the greater total

resilience, or requires a greater amount of *work* to be done on it to produce rupture. Here, then, are five independent points of superiority of the piece B over the piece A, while the bare record of items 1, 2, and 3, given above, would indicate the reverse.

The graphic method of recording results is now adopted by all scientific experimenters. The simplicity and accuracy of the method should commend its use also in ordinary tests for commercial purposes.

COMPRESSIVE STRESS.

A compressive stress, or push, applied to a piece of material is a force which tends to shorten it. In testing the compressive resistance of metals or other materials, testing machines similar to those used in tests of tensile resistance are used, or the tensile machine may be adapted to compressive tests by means of a couple of yokes or like mechanical device.

What is meant by the term "compress-

ive strength" has not yet been settled by the authorities, and there exists more confusion in regard to this term than in regard to any other used by writers on strength of materials. The reason of this may be easily explained. The effect of a compressive stress upon a material varies with the nature of the material, and with the shape and size of the specimen tested. While the effect of a tensile stress is always to produce rupture or separation of particles in the direction of the line of strain, the effect of a compressive stress on a piece of material may be either to cause it to fly into splinters, to separate into two or more wedge-shaped pieces and fly apart, to bulge, buckle or bend, or to flatten out and utterly resist rupture or separation of particles. A piece of speculum metal under compressive stress will exhibit no change of appearance until rupture takes place, and then it will fly to pieces almost as suddenly as if blown apart by gunpowder. A piece of cast iron or of stone will generally split into wedge-

shaped fragments. A piece of wrought iron will buckle or bend. A piece of wood or of zinc may bulge, but its action will depend upon its shape and size. A piece of lead will flatten out and resist compression till the last degree; that is, the more it is compressed the greater becomes its resistance.

Air and other gaseous bodies are compressible to any extent, as long as they retain the gaseous condition. Water, not confined in a vessel, is compressed by its own weight to the thickness of a mere film, while when confined in a vessel it is almost incompressible. It is probable, although it has not been determined experimentally, that solid bodies when confined are at least as incompressible as water. When they are not confined, the effect of a compressive stress is not only to shorten them, but also to increase their lateral dimensions or bulge them. Lateral strains are therefore induced by compressive stresses.

The weight per square inch of original

section required to produce any given amount or percentage of shortening of any material is not a constant quantity, but varies with both the length and the sectional area, with the shape of this sectional area, and with the relation of the area to the length. The "compressive strength" of a material, if this term be supposed to mean the weight in pounds per square inch necessary to cause rupture, may vary with every size and shape of specimen experimented upon. Still more difficult would it be to state what is the "compressive strength" of a material which does not rupture at all, but flattens out. Suppose we are testing a cylinder of a soft metal like lead, two inches in length and one inch in diameter, a certain weight will shorten it one per cent., another weight ten per cent., another fifty per cent., but no weight that we can place upon it will rupture it, for it will flatten out to a thin sheet. What then is its compressive strength? Again, a similar cylinder of soft wrought iron would probably com-

press a few per cent., bulging evenly all around, it would then commence to bend, but at first the bend would be imperceptible to the eye and too small to be measured. Soon this bend would be great enough to be noticed, and finally the piece might be bent nearly double, or otherwise distorted. What is the "compressive strength" of this piece of iron? Is it the weight per square inch which compresses the piece one per cent., or five per cent., that which causes the first bending (impossible to be discovered), or that which causes a "perceptible" bend?

So confusing is this whole matter of compressive strength that there is scarcely a single published figure on the compressive strength of wrought iron that can be relied upon. Wood's resistance of materials has the following:

"Comparatively few experiments have been made to determine how much wrought iron will sustain at the point of crushing. Hodgkinson gives 65,000, Rondulet 70,800, Weisbach 72,000, Ran-

kine 30,000 to 40,000. It is generally assumed that wrought iron will resist about two-thirds as much crushing as to tension, but the experiments fail to give a very definite ratio."

Mr. Whipple, in his treatise on bridge building, states that a bar of good wrought iron will sustain a tensile strain of about 60,000 pounds per square inch, and a compressive strain, in pieces of a length not exceeding twice the least diameter, of about 90,000 pounds.

In a "Pocket Companion" of tables appertaining to the use of wrought iron, published by Carnegie Bros. & Co., of Pittsburgh, the following values are given in a table of crushing strength of materials, said to be deduced from the experiments of Major Wade, Hodgkinson, and Capt. Meigs:

American	wrought	iron,	127,720	lbs.
"	"	" mean	83,500	"
English	"	"	65,200	"
			40,000	"

On the page next after this table is the following:

"Experiments upon wrought iron give a mean crushing stress [strength] of 74,250 lbs. per square inch."

When the best authorities differ so widely in their views of the compressive strength of wrought iron, can it be wondered that engineers have so long hesitated to use the material in compression, and that when they do use it they dare not use it with economy? If the United States Board appointed to test Iron and Steel, which seems to be about to close its labors for want of an appropriation to continue them, were to do nothing else than investigate this matter of the compressive strength of wrought iron, and establish rules governing its use to resist compressive forces in structures, they would confer a benefit on the country and the world which would be worth ten times the amount of the appropriation necessary for the whole work.

Stoney states that the strength of short pillars of any given material, all having the same diameter, does not vary

much, provided the length of the piece is not less than one, and does not exceed four or five diameters, and that the weight which will just crush a short prism whose base equals one square inch, and whose height is not less than 1 to $1\frac{1}{2}$ and does not exceed 4 or 5 diameters, is called the *crushing strength* of the material. It would be well if experimenters would all agree upon some such definition of the term "crushing strength," and insist that all experiments which are made for the purpose of testing the relative values of different materials in compression be made on specimens of exactly the same shape and size. An arbitrary size and shape should be assumed and agreed upon for this purpose. The size mentioned by Stoney is definite as regards area of section; *viz.*: one square inch, but is indefinite as regards length; *viz.:* from 1 to 5 diameters. In some metals a specimen 5 diameters long would bend, and give a much lower apparent strength than a specimen having a length of 1 diameter.

The words "will just crush" are also indefinite for ductile materials, in which the resistance increases without limit if the piece tested does not bend. In such cases the weight which causes a certain percentage of compression, as five, ten, or fifty per cent. should be assumed as the crushing strength.

For future experiments on crushing strength, three things are desirable; first, an arbitrary standard shape and size of test specimen for comparison of all materials; secondly, a standard limit of compression for ductile materials, which shall be considered equivalent to fracture in brittle materials; thirdly, an accurate knowledge of the relation of the crushing strength of a specimen of standard shape and size to the crushing strength of specimens of all other shapes and sizes. The latter can only be secured by a very extensive and accurate series of experiments upon all kinds of materials, and on specimens of a great number of different shapes and sizes. Hodgkinson has been the chief experi-

menter in this direction, but his researches have not been nearly so extensive as to give us all the desirable information on this point. A standard size for compression tests, and a standard limit of compression, assumed equivalent to fracture, have never yet been agreed upon and have probably never even been proposed.

The writer proposes, as a standard shape and size for a compressive test specimen for all materials, a cylinder one inch in length, and one half square inch in sectional area, or 0.798 inch diameter; and for the limit of compression equivalent to fracture, ten per cent. of the original length. The term "compressive strength," or "compressive strength of standard specimen," would then mean *the weight per square inch required to fracture by compressive stress a cylinder one inch long and* 0.798 *inch diameter, or to reduce its length to* 0.9 *inch if fracture does not take place before that reduction in length is reached.* If such a standard, or any standard size

whatever, had been used by the earlier authorities on the strength of materials, we never would have had such discrepancies in their statements in regard to the compressive strength of wrought iron as those given above

The reasons why this particular size is recommended are, that the sectional area, one half square inch, is as large as can be taken in the ordinary testing machines of 100,000 pounds capacity, to include all the ordinary metals of construction, cast and wrought iron and the softer steels; and that the length, one inch, is convenient for calculation of percentage of compression. If the length were made two inches many materials would bend in testing, and give incorrect results. Even in cast iron, Hodgkinson found as the mean of several experiments on various grades, tested in specimens $\frac{3}{4}$ inch in height, a compressive strength per square inch of 94,730 pounds, while the mean of the same number of specimens of the same irons tested in pieces $1\frac{1}{2}$ inches in height, was only 88,800

pounds. The best size and shape of standard specimen should, however, be settled upon only after consultation and agreement among several authorities. The United States Board appointed to test Iron, Steel, etc., or the American Society of Civil Engineers might easily fix upon such a standard.

After fixing upon a standard test piece, by which all materials might be compared, tests should be made of all sizes and shapes other than the standard, to determine what relation existed between their apparent strength per square inch and that of the standard. When these results were obtained and formulated, a test might be made of any material of any shape and size, and by applying the formulæ of reduction, the "compressive strength of standard specimen" be predicted, and from the latter could be calculated the strength of any shape and size which it might be proposed to use in a structure.

Some of the results already obtained in the direction of determining the rela-

tion of length and diameter to apparent compressive strength will now be given; taken chiefly from Wood's Resistance of Materials.

As above stated, in Hodgkinson's experiments the increase of the length of test specimens decreased the apparent compressive strength per square inch from 94,730 to 88,800 pounds.

Fairbairn and Tate, in testing small cubes and cylinders of glass, found a compressive strength for the cubes of 18,401 and for the cylinders of 30,153 pounds per square inch.

Hodgkinson, in experiments on long square pillars, found that the compressive strength varied as the 3.59 power of the side of the square, as a mean result; the extremes being the 2.69 and the 4.17 powers. From his experiments, the following table of the absolute strength of columns was obtained, in which

P=crushing weight in gross tons.

d=the side of the column in inches, or external diameter.

Kind of column.	Both ends rounded, the length of the column exceeding 15 times its diameter.	Both ends flat, the length of the column exceeding 30 times its diameter.
Solid cylindrical columns of cast iron..........	$P=14.9\frac{d^{3.76}}{l^{1.7}}$	$P=44.16\frac{d^{3.55}}{l^{1.7}}$
Hollow cylindrical columns of cast iron	$P=13\frac{d^{3.76}-d_1^{3.76}}{l^{1.7}}$	$P=44.34\frac{d^{3.55}-d_1^{3.55}}{l^{1.7}}$
Solid cylindrical columns of wrought iron......	$P=42\frac{d^{3.76}}{l^2}$	$P=133.75\frac{d^{3.55}}{l^2}$
Solid square pillar of Dantzic oak..........	....	$P=10.95\frac{d^4}{l^2}$

d_1 = the internal diameter of the hollow, in inches.

l = the length in feet.

The above formulas apply only in cases in which the length is so great that the column breaks by bending and not by simple crushing. If the column be shorter than that given in the table, and more than four or five times its diameter, the strength is found by the following formula:

$$W = \frac{PCK}{P + \frac{3}{4}CK}$$

in which

P = the value given in the preceding table.

K = the transverse section of the column in square inches.

C = the modulus for crushing in gross tons per square inch.

W = the strength of the column in gross tons.

The "modulus of crushing" is defined by Prof. Wood as "the pressure which is necessary to crush a piece of any materi-

al whose section is unity and whose length does not exceed from one to five times its diameter"—a very indefinite quantity, as already shown in the case of wrought iron!

Prof. Wood states that it is found by experiment that the resistance of short pieces (blocks) to crushing varies nearly as the transverse section of the piece. Gen. Gillmore, however, in experiments on stone, found that the strength per square inch of section of cubes of different sizes varied nearly as the cube root of the side of the cube.

In some experiments made by Mr. J. Tangye on the compressive strength of wrought iron, a bar of soft Lowmoor iron, 8 or 9 inches long, was planed on opposite sides to a thickness of $\frac{3}{4}$ inch, and subjected to pressure on one side under a steel die $\frac{1}{2}$ inch square. The following are the results of the tests, and they prove clearly that a unit of iron has a much greater power of resistance when it forms part of a large mass than when it is isolated in the manner customary in experiments on compression:

Load per square inch.

20 tons,		no impression.
24	"	slightest indentation, sensible to finger nail.
28	"	indentation visible, edge fol lowed by finger nail.
40	"	indented about $\frac{1}{64}$th of an inch.

These experiments certainly throw a doubt upon the statement that the resistance of short pieces varies as the transverse section.

Gordon's Rules for Flexible Columns. (From Clark).—The first and second formulas given below were deduced by Lewis D. Gordon, from the results of Hodgkinson's experiments. As here given, they show the total breaking weight of a cast iron column. The succeeding formulas for strength of columns of wrought iron and steel were constructed on the basis of Gordon's formula by the authorities named.

For solid or hollow round cast iron columns $W = \dfrac{36a}{1 + \frac{r^2}{400}}$

For solid or hollow rectangular cast iron columns $W=\frac{36a}{1+\frac{r^2}{500}}$

For solid rectangular wrought iron columns $W=\frac{16a}{1+\frac{r^2}{3000}}$ (Stoney).

For columns of angle, tee, channel, or cruciform iron $W=\frac{19a}{1+\frac{r^2}{900}}$ (Unwin).

For solid round column of mild steel

$W=\frac{30a}{1+\frac{r^2}{1400}}$ (Baker).

For solid round column of strong steel

$W=\frac{51a}{1+\frac{r^2}{900}}$ (Baker).

For solid rectangular column of mild steel $W=\frac{30a}{1+\frac{r^2}{2480}}$ (Baker).

For solid rectangular column of strong steel $W=\frac{51a}{1+\frac{r^2}{1600}}$ (Baker).

In these formulas W=the breaking weight in tons of 2240 lbs., a=sectional area of the material in square inches, r= the ratio of the length to the diameter, the diameter being the least dimension of the section or that in which it is most flexible.

The pocket book of Carnegie Bros. & Co. (mentioned above) gives a formula for the strength of wrought iron columns, based upon Gordon's formula as follows:

$$W=\frac{FA}{1+\frac{1}{4500}\left(\frac{l}{h}\right)^2}:$$

in which W=breaking load in pounds, F=36000 pounds, A=sectional area of column in square inches, l=its length in inches, and h=its diameter in inches.

A similar pocket book, by the Phœnix Iron Co., of Philadelphia, gives the formula in this shape:

$$W=\frac{FA}{1+\frac{1}{3000}\left(\frac{l}{h}\right)^2}$$

in which F=50000 pounds.

The following example will show the discrepancies in results obtained by these two formulas and the one of Stoney:

Given a wrought iron column one inch square in section and ten inches long. Required its breaking weight?

$$A=1 \text{ square inch. } \frac{l}{h}=r=10. \ r^2=100.$$

$$W=\frac{16\times1}{1+\frac{100}{3000}}=15.489 \text{ tons}=34{,}695 \text{ lbs.}$$

(Stoney).

$$W=\frac{36000\times1}{1+\frac{100}{4500}} = \ldots\ldots \ 35{,}218 \text{ lbs.}$$

(Carnegie Bros. & Co).

$$W=\frac{50000\times1}{1+\frac{100}{3000}} = \ldots\ldots\ldots \ 48{,}389 \text{ lbs.}$$

(Phœnix Iron Co).

showing a difference of nearly 40 per cent. between the lowest and highest results. The columns of a building which were designed with the use of one of these formulas might cost 40 per cent. more than if designed with the use of another.

Enough has now been given to show that our knowledge of the subject of compressive strength is very indefinite and unreliable. The greatest necessity exists for a comprehensive series of experiments which shall serve as a standard for reference and comparison. Such experiments would be too costly to be undertaken by any individual, and as the matter is of national importance, it is well worthy the attention of the government.

In making experiments upon compressive strength, even greater care is required than in experiments on tensile strength. In tensile tests, the tendency of a ductile specimen is always to pull into the line of strain, and this to some extent (but not entirely) corrects the error caused by wrongly placing the piece in the testing machine. In compressive tests the tendency is just the reverse; the effect of a push is always to cause the piece to tend to bend out of the line of strain, and this can only be prevented by having the line of strain

pass exactly through the axis of the specimen. The test specimen should, therefore, be placed in the machine with the utmost accuracy, care should be taken that the bearing of the piece on the compression blocks is a true one, and that in pulling or pushing together the compression blocks they shall have no tendency to move sidewise or in any other direction than that of the line of strain.

TRANSVERSE STRESS.

Tests by transverse stress are in general much more easily made than tests by either tensile or compressive stress. An elaborate testing machine is not necessary. The bar or beam to be tested is placed on two supports, which are a measured distance apart and perfectly level, and weights applied to the middle till the piece breaks. Steel rollers are frequently used for supports, rolling on a horizontal plane and kept a constant distance apart during the test. The use of rollers obviates the error due to friction of the bar upon the supports when the latter are fixed.

In testing bars which require considerable weight to break them, some mechanical appliance has to be used to assist in placing the weights on the bar without shock. A testing machine, designed for transverse tests alone, built by Messrs. E. & T. Fairbanks & Co. for the Mechanical Laboratory of the Stevens Institute of Technology, consists of an ordinary platform scale, with a heavy timber foundation, carrying a heavy cast iron beam with two cast iron supports which may be placed any distance apart up to five feet. The bar to be tested rests on rollers, and the pressure is applied by means of a screw. This machine was largely used in the experiments on strength of alloys, made by the United States Board appointed to test iron, steel, etc., and a complete description of it will appear in the report on these tests when published. It has been used up to 7,000 pounds pressure, and it will test bars up to five feet in length. Measurements of deflection are made to the $\frac{1}{10000}$ of an inch by means of the micrometer screw

apparatus, with electrical contact, which was described under the head of tensile tests. By this machine and measuring apparatus very important scientific results have been obtained in reference to the effect of time upon tests, in elevating the elastic limit and in causing increase of deflection and decrease of set, which are described at length by Prof. Thurston in the Transactions of the American Society of Civil Engineers, 1875 and 1876.

The new 40,000 pound tensile testing machines, built by Riehle Bros. of Philadelphia, have attachments by which transverse tests may be made on bars 12 inches in length between supports, and the new 100,000 pound machine of John L. Gill, Jr., of Pittsburgh, has a transverse attachment that will take a bar of any length from 10 to 40 inches. The manufacturers of wrought iron beams have had tests made and published in their "pocket books of information" on the transverse strength of their beams, the results of which tests may in general

be relied on for practical purposes. There exists no such discrepancy in published figures of transverse strength of beams as that which has been shown to exist in figures of the compressive strength of columns.

In recording results of transverse tests, it is important sometimes to note the time taken in the tests. A remarkable instance of the increase of apparent strength of wrought iron, by keeping it under strain for three weeks, has already been noted in discussing the influence of time upon tensile tests. Bars of tin and of ductile alloys will show a much less transverse strength if considerable time is taken in testing than if the test is made rapidly, while the reverse is true in tests of wrought iron and soft steel.

The effect of time in a transverse test varies according to the method of testing. In testing by dead loads the load remains constant, and if the bar is strained beyond its elastic limit the deflection may increase with time. This increase of deflection may continue for several

minutes or for several days and then entirely cease; or it may continue with increasing rapidity until the bar breaks or bends. In Prof. Thurston's tests by transverse stress some curious phenomena have been observed. The rate of increase of deflection in some instances grew smaller and smaller for several hours, then for a while it remained constant, and then increased till the bar broke. It would appear as if there was a certain definite deflection for each material, after passing which a continuance of the load which caused it will increase the deflection indefinitely, at an increasing rate, until bending or rupture takes place, but that before that deflection is reached the rate of increase of deflection will be a decreasing one, tending to a cessation of that increase.

In testing by a pressure screw and platform scale, or similar testing machine, the action of a dead load is imitated only when the machine is so operated as to keep the scale beam constantly balanced, the deflection meanwhile in-

creasing, as the pressure screw requires to be advanced to keep the beam balanced. If the pressure screw is not advanced, and the deflection is therefore held constant, the bar will exhibit a decrease of resistance to that deflection, which decrease, in every ductile and non-elastic material, will continue with a decreasing rate until the deflection has become a permanent set, and the scale beam indicates no resistance at all; in elastic materials the decrease of resistance will soon cease, and the bar, acting like a perfect spring, will keep the scale beam balanced at a figure somewhat below that indicating the load which primarily caused the deflection. In a perfectly elastic material, as hard steel or glass, no decrease of resistance (or only a very slight one) takes place. The study of these phenomena opens an interesting and almost unexplored field of physical research.

A standard size and shape of test specimen would be desirable for transverse tests, but it is not so necessary as

in compressive or tensile tests, since the relation existing between the dimensions of bars and both their ultimate strength and deflection under loads has been determined, both mathematically and by experiment. The strength of bars of rectangular section is found to vary directly as the breadth of the specimen tested, as the square of its depth, and inversely as its length. The deflection under any load varies approximately as the cube of the length, and inversely as the breadth and as the cube of the depth. Represented algebraically, if S=the strength and D the deflection, *l* the length, *b* the breadth, and *d* the depth.

$$S \text{ varies as } \frac{bd^2}{l} \text{ and } D \text{ varies as } \frac{l^3}{bd^3}.$$

For the purpose of reducing the strength of pieces of various sizes to a common standard the term *modulus of rupture* (represented by R) is used. Its value is obtained by experiment on a bar of rectangular section supported at the ends and loaded in the middle and sub-

stituting numerical values in the following formula

$$R = \frac{3}{2}\frac{Pl}{bd^2} \text{ in which}$$

P=the breaking load in pounds, l=the length in inches, b the breadth, and d the depth.

The *modulus of rupture* is sometimes defined as the strain at the instant of rupture upon a unit of the section which is most remote from the neutral axis on the side which first ruptures. This definition, however, is based upon a theory which is yet in dispute among authorities, and it is better to define it as a numerical value found by application of the formula above given.

Knowing the value of R for any material the weight necessary to break a beam of that material, loaded in any of the ways specified below may be found from the following formulas:

For a beam fixed at one end and a load P at the other

$$P = \frac{1}{6}\frac{Rbd^2}{l} \qquad (1)$$

The same beam with a load W uniformly distributed over the length

$$\tfrac{1}{2}W=\tfrac{1}{6}\,\frac{Rbd^2}{l} \qquad (2)$$

Beam supported at its ends and loaded in the middle

$$P=\tfrac{2}{3}\,\frac{Rbd^2}{l} \qquad (3)$$

Beam supported at its ends and loaded uniformly

$$P=\tfrac{4}{3}\,\frac{Rbd^2}{l} \qquad (4)$$

Beam fixed at both ends and loaded in the middle

$$P=\tfrac{4}{3}\,\frac{Rbd^2}{l} \qquad (5)$$

Beam fixed at both ends and loaded uniformly

$$P=\frac{2Rbd^2}{l} \qquad (6)$$

These formulas are all deduced mathematically (see Wood's Resistance of Materials) and are confirmed by experiment, except the last two, in which it seems that the mathematical investigation has not in-

cluded all the conditions, for Mr. Barlow found by experiment that equation (5) should be $P=\frac{Rbd^2}{l}$.

The value of R for any material depends upon the tensile and the compressive strength, and if these (per square inch) are not equal it is always greater than the one and less than the other. In testing a beam by transverse stress (supported at the ends) the upper side is compressed and the lower side is extended, the surface located at some position between the compressed and extended sides, which receives no strain, being called the neutral axis, or neutral surface.

The strength of beams of other than rectangular section, the deflection of beams of various shapes and sizes, the relation existing between transverse strength and tensile and compressive strength, and many other interesting branches of the subject of transverse strength are treated of at great length by various authorities, but the limits of this

paper will not allow of more than a mere mention of them here. A recent work entitled "Transverse Strain," by R. G. Hatfield, is an invaluable book for architects and others interested in the subject of which it treats, who are not profes sional engineers. Various theories of the relation between transverse strength and tensile and compressive strength are found in works on resistance of materials. A theory on this subject is given by the writer in a note published in VAN NOSTRAND'S MAGAZINE, October, 1877.

SHEARING STRESS.

Shearing stress is a force tending to draw one part of a solid substance over another part of it; the applied and resisting forces acting in parallel planes which are very near to each other. It acts like a pair of shears. Materials under a variety of circumstances are subjected to this stress—as rivets in riveted plates, pins and bolts in spliced joints, beams subjected to transverse stress, bars which are twisted, and in

short all pieces which are subjected to any kind of distorsive stress in which all parts are not equally strained. Shearing may take place in detail, as when plates or bars of iron are cut with a pair of shears, when only a small portion is operated upon at a time; or it may be done so as to bring into action the whole section at a time, as in the process of punching holes into metal, where the whole convex surface of the hole is supposed to resist uniformly.*

The total resistance to ultimate shearing, when all parts of the resisting surface are brought into action at once, is found to vary directly as the section. The experiments on large sections, however, have not been sufficiently numerous to make this certain for all cases. From a table of shearing strength of various metals, given in Wood's "Resistance of Materials," on the authority of various experimenters, it appears that the shearing strength of wrought iron is about the same as its tenacity, of cast

* Wood's "Resistance of Materials."

steel it is a little less than its tenacity, of cast iron it is double its tenacity and about $\frac{2}{5}$ its crushing resistance, and of copper it is about $\frac{2}{3}$ its tenacity. Clark considers that the shearing strength of wrought iron may be taken at about $\frac{4}{5}$ of its tenacity. Clark also gives the following: "Rankine states that the shearing strength of cast iron is 12.37 tons per square inch; Stoney found by experiment, that it varied from 8 to 9 tons per square inch. Both may be correct, as cast iron is very variable in tensile strength. It is probable that its shearing resistance is by reason of its compar ative incompressibility equal to its direct tensile resistance."

Engineer-in-Chief William H. Shock, U. S. N., found that the shearing resistance of ordinary round bar iron of commerce averaged 17.81 tons, or 39894 pounds per square inch, on bolts of from $\frac{1}{2}$ inch to 1 inch diameter.

M. C. Little found the resistance to shearing by parallel cutters of bars 3 inches by $\frac{1}{2}$ inch and 1 inch thick, and to

punching 1 and 2 inch holes through bars $\frac{1}{2}$, 1 and $1\frac{1}{2}$ inches thick, varied from 19 to 22.35 tons per square inch of area cut.

In view of the conflicting statements given above, it may well be supposed that our knowledge on the subject of shearing resistance is almost as indefinite as that of compressive resistance. Some light is thrown upon the reason of the discrepancies by the following fact, taken from Clark:

"Oak treenails firmly held, of from 1 to $1\frac{3}{4}$ inch diameter, were found by Mr. Parsons to have a shearing strength of about two tons per square inch of section. For the development of so much resistance, Rankine deduces that the planks connected by the treenails should have a thickness of at least three times their diameter. Treenails of $1\frac{3}{4}$ inches diameter in a three inch plank, bore only 1.43 tons per square inch, and in a six inch plank 1.73 tons."

Here it is plainly shown that the strength of the treenail depended not

only on its diameter, but also on the bearing it had in the plank, and it seems almost certain, therefore, that the varying firmness of the bearings used by different experimenters has been the cause of the discrepancies in their results. The following illustration may show how different results might be obtained on the same piece of iron:

A represents a case of true double shearing. The iron bolt is being sheared off directly in the lines of the sliding surfaces aa' and bb', the sliding plates being of hardened steel with true corners. Test B might appear exactly like test A to the ordinary observer if the bending, which is exaggerated in the cut, were very slight. The only difference here is, that the sliding plates are of soft iron, and the bolt fits itself to a bearing along the lines cc', and the result is a combination of tensile, shearing and bending stresses. It would be impossible to say from such a test as this, what the actual shearing strength of the bolt would be. C represents a case of single

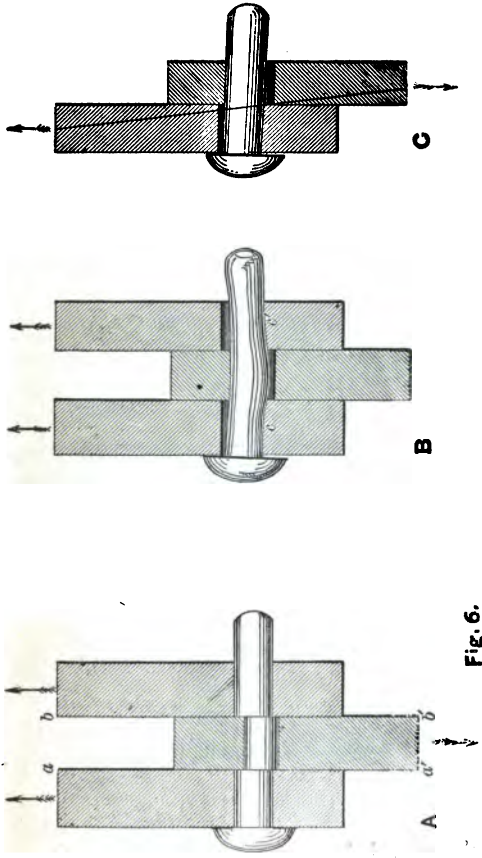


Fig. 6.

shearing in which plates of soft iron are used with a similar effect to that shown in B, but still worse. The dotted line shows that the line of strain of the testing machine is at an angle to the line of sliding, which further complicates the result.

A committee of the American Railway Master Mechanics' Association, made the following experiments on riveted plates:

Six pieces $1\frac{3}{4}$ inches wide and $\frac{5}{16}$ inch thick, cut from the same sheet, were punched and riveted together with the best $\frac{5}{8}$ inch rivets, one rivet to each pair, with the following results:

	lbs.
No. 1 broke in center line of hole under	17,828
No. 2 " " " "	17,828
No. 3 " " " "	17,143
The average breaking strain being	17,599

Six pieces, duplicates of those last mentioned, were *drilled* and riveted together, one $\frac{5}{8}$ inch rivet to each pair.

No. 1 *sheared the rivet* under	17,143	lbs.
No. 2 " "	16,457	"
No. 3 " "	15,428	"
The average *shearing* strain being	16,342	

Prof. Wood remarks concerning these tests, that "it is evident that drilled holes cause the rivets to be sheared more easily than punched ones." If these sets of tests are considered as tests of the strength of ⅝ inch rivets, the latter set show the rivets to have an average strength of 16,342 pounds, or 53,231 pounds per square inch, while the former shows their average to be *more than* 17,599 pounds, or 57,326 pounds per square inch. Different methods of testing, therefore, give different results. Which is the correct method? And how many tests of which the results are published were made by the correct method?

The writer is not aware that any standard method of making tests of shearing strength, or standard size of test specimens, has ever been proposed. For testing the transverse shearing strength of bolts and rivets, the use of the double shearing plates, shown at A Fig. 6, is probably the best method; the plates being made of hardened steel, and

the holes drilled in them just large enough to allow the bolt to enter with a sliding fit. The best thickness of the plates or the relation of thickness to the diameter of the holes would have to be determined by experiment before the proper standard could be fixed, as the tests of treenails by Mr. Parsons, above mentioned, show that the thickness of the bearing has an influence upon the results. As it is not entirely certain that the resistance of various sections of the same material to shearing stress is exactly proportional to the area of section, experiments to determine the relation of shearing resistance to area of section and to determine the best size and shape for a standard test specimen are needed, in order that the results obtained by differ ent experimenters may be compared.

It has been stated above that in the process of punching metal the "whole convex surface of the hole is supposed to resist uniformly." This is probably true only in punching thin plates. In punching bars, blocks or nuts whose thickness

exceeds the diameter of the punch, it is found that the punch may be entered into the upper side of the metal a considerable distance before the lower side of the plate shows any signs of being strained. This was plainly shown in some experiments on punching made by Mr. David Townsend, published in the *Journal of the Franklin Institute*, for March, 1878. In these experiments rectangular blocks of iron $1\frac{3}{4}$ inches thick were punched only partly through, and then, after withdrawing the punch and planing away one-half of the metal to a plane passing through the axis of the hole, it was found that the effect of the partial punching was to crowd the portion of metal displaced by the punch into those portions beneath and around the hole, but that when the punch had not entered more than half the thickness of the block the fibers of the metal at the bottom of the block appeared to be uninfluenced in any way by the punching. It seems evident from these experiments that the resistance to punching is not

simply resistance to shearing, but is compounded with compressive resistance, and that the convex surface of the hole therefore does not resist uniformly and simultaneously, but to some extent in detail, or one portion after the other.

It would appear probable, also, that in shearing large bolts, or large sections of any kind, that the whole section may not resist simultaneously. If this is the case large sections would show a less apparent shearing strength per square inch than small sections. The relation of resistance to section may also vary with the nature of the material.

It is plain that the subject of shearing strength is a complex one, and further experiments are required to render our knowledge upon it at all definite and reliable.

TORSIONAL STRESS.

A torsional stress applied to a piece of material is a force that tends to turn or twist it. In all cases in which a force is applied at one point on a shaft to turn it, and there is a resisting force at another

point, the shaft is subjected to torsional strain. The wheel and axle is an example. To produce torsion without bending, a *couple*, whose axis coincides with the axis of the piece, must be applied to it. If only a single force is applied, the result is a combined bending and twisting. A hand-wheel, operated by two hands placed exactly opposite on the rim, and each hand exerting the same effort to turn the wheel, is an example of the application of a couple. A hand-wheel operated by only one hand on the rim is an example of the application of a combined bending and twisting force.

A torsional stress tends to break a piece by combined shearing and tensile stresses. In twisting a rope, for instance, it is plainly seen that rupture will take place by tension of the fibers. In twisting certain metals, such as soft steel, the piece appears to break chiefly by shearing, the fracture being a comparatively plane surface, perpendicular to the axis of the piece.

The exact relation between torsional

strength and tensile and shearing strength has not yet been determined, but approximate theoretical relations may be derived mathematically, and still closer approximations to the true relations may be obtained by experiment. The relation varies with the ductility of the material. In a material which is perfectly elastic until rupture the resistance of each fiber varies directly as its distance from the axis of the piece. In a material which is very ductile, the final resistance of each fiber is nearly the same, whatever its distance from the axis of the piece. Of two pieces of metal of the same size and the same tensile and shearing strength, the one which is the more ductile will offer the greater resistance to torsion.*

* Recent Experiments by Prof. Thurston throw a doubt upon the accuracy of this statement. He remarks: "It singularly happens that the commonly accepted theory predicts values of this relation [between tension and torsion] which are not only incorrect but which are, for different cases, precisely the opposite in their mutual relations to those given by experiment." In confirmation he gives the relations between tension and torsion for cast iron, wrought iron and steel, of various degrees of ductility. See Transactions Am. Soc'y of Civil Engineers, July, 1878, Vol. VII p. 169.

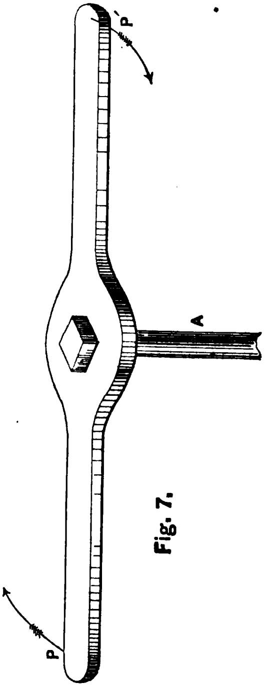


Fig. 7.

Resistance to torsion is expressed in terms of *moment*, or force multiplied by distance, as foot pounds. The amount of force P necessary to twist the head off

the bolt shown in the cut, will depend upon the distance from the axis of the bolt at which the force P (or the couple PP′) is applied to the wrench handle. If it is applied at two feet from the axis, it will take only half as much force as if it is applied at one foot from the axis, but the product of pounds into feet, or "foot pounds," will be the same.

The resistance to torsion of a cylinder of any material, varies as the cube of its diameter. A demonstration of this fact may be found in Wood's "Resistance of Materials," page 208. The following formulas are given:

$$Pa=\tfrac{1}{2}\pi Jr^3, \text{ for brittle materials} \quad (1)$$
$$Pa=\tfrac{2}{3}\pi Jr^3, \text{ for ductile materials} \quad (2)$$

in which P is the force applied at the distance a, the product Pa being the moment, usually expressed in foot pounds, π equals 3.1416, r is the radius of the cylinder, and J the *modulus of torsion,* a quantity which is found by experiment, and varies with each material. Formula (1) is based on the suppo-

sition that the resistance of each fiber varies directly as its distance from the center, and formula (2) on the supposition that the resistance of each fiber is the same. Both formulas are deduced mathematically, by processes which may be found in Wood's "Resistance."

In experiments on cylindrical specimens, to obtain merely the torsional strength of a material, the quantity Pa is found, and from the result of the expériment the quantity $\frac{1}{2}\pi J$ (or $\frac{2}{3}\pi J$) is calculated, which is the strength of a piece of one inch radius or two inches diameter. Having this quantity, or modulus, the strength of any cylindrical piece of the same material is found by multiplying the modulus by the cube of the radius.

Prof. R. H. Thurston has recently invented a testing machine which determines the strength, ductility, resilience and homogeneity of materials by torsional strain. A complete description of this machine, with an account of results obtained by it may be found in a

paper by the inventor, published in the *Journal of the Franklin Institute* in 1874.* The principal features of the machine which recommend its adoption for general use are, its extreme simplicity and cheapness, its convenience of operation and its autographic registry. By the latter a strain diagram is made, which shows the resistance of the material at every instant of the test. The value of the graphic method of recording tests has already been shown, in treating of tests by tensile stress, and the automatic graphic record of this machine is especially valuable, as it is more accurate than any plotted diagram.

The autographic record of a torsional test of any material is almost precisely similar to a strain diagram made by plotting the results of a tensile test, as shown in the plate given with the discussion of tensile stress; but the vertical distances of any point of the curve from the base line represent foot pounds of moment, and the horizontal

* *Van Nostrand's Magazine*, Vol. XI.

distances from a vertical line at the origin represent angles of torsion. As in the plotted diagrams the vertical distances indicate strength, the horizontal distances ductility, the inclination of the initial portion of the curve from the vertical is a measure of the coefficient of elasticity, the point at which the curve begins to bend toward the horizontal marks the limit of elasticity, the area included between the curve and the base line measures the work done upon the specimen in breaking it, or the resilience, and the regularity of the curve indicates the homogeneity of the material. The strength, expressed in foot pounds of moment, has a direct relation to the tensile strength, varying somewhat with different kinds of material, and when this relation is known, the distance of the curve from the base line is a measure of tensile strength with a sufficient approximation to correctness for nearly all practical purposes. The ductility, expressed in the angle of torsion, has a direct relation to the extension of the

exterior fibers of the specimen, depending upon the size of the latter, hence the angle of torsion is a measure of extension. It is thus seen that a test by torsional stress of any material can be made to give a record of all the qualities which render it available in construction. This is done by Prof. Thurston's machine with the utmost convenience and accuracy. The writer has made several hundred tests with this machine and can therefore speak from experience. It is now in use in several manufacturing establishments and institutions of learning. A torsion machine, somewhat similar to that of Prof. Thurston, but lacking the feature of automatic registry, has been invented by W. E. Woodbridge, M. D. It was used by the inventor in an extensive series of experiments on steel wire, the results of which, with a plate and description of the machine, are given in a report by him to the government.*

* "Report on the Mechanical Properties of Steel, chiefly with reference to Gun Construction on the Woodbridge system." By W. E. Woodbridge, M.D. Appendix F. to the report of the Chief of Ordnance. Washington, 1875.

The writer is not aware that this machine has been used by other experimenters, but it appears to be well designed, and capable of doing accurate work.

RESISTANCE TO CONTINUED AND TO REPEATED STRESSES, TO SUDDEN SHOCKS AND TO VIBRATIONS.

The preceding discussions have chiefly had relation to the strength of materials as determined by tests of limited duration, and in which the stress is usually applied gradually or without suddenness, and repeated but a few times, if at all.

The conditions to which materials of construction are subjected when in actual use are quite different in some respects from those to which the test specimen is subjected. They have to endure uniform strains through many years, or many centuries, as in buildings; uniform strains, with variable strains and sudden shocks at intervals, as in bridges; rapidly recurring strains of different kinds repeated millions of times, as in reciprocating parts of machinery; incessant

tremors and vibrations, as in railroad cars; and sometimes every variety and combination of all of these.

As it is manifestly impossible to subject a material to a test which shall fulfill all the conditions of actual use, it is desirable to know what relation exists between the resistance of each variety of material used in construction to steady strain applied for a limited period, to its resistance to continued or repeated stresses, to sudden shocks, and to tremors or vibrations. Thus questions like these may arise: If a rod of iron one inch square in section will resist a steady pull of 50,000 pounds for one hour or one day without breaking, what steady pull will it resist without breaking for a hundred years? What load will it resist for a hundred years if one-half the load is gradually placed on and taken off the rod a certain number of times each day? What load will it resist if applied suddenly? What load will it resist if the suddenly applied load is repeated a number of times, say a million or a bil-

lion times? What load will it resist if the load falls a certain number of feet before striking? What load will it resist if this load falls a certain distance a certain number of times? These and a hundred similar questions might be asked concerning this one rod of iron, and the same might be asked of rods of all kinds of material and of all sizes.

The field of inquiry here presented is almost illimitable, but it is an eminently practical one. Materials of construction are used every day which are subjected to just such various conditions as those above mentioned, but the only knowledge we have concerning the resistance of these materials is that derived from tests of small specimens for a limited time, and that derived from observations of materials in use under similar circumstances. On some of these points our knowledge is already definite enough for all practical purposes. Thus it is safe to assume that a stone pillar, resting on a stone foundation, that supports a certain load for one day will support it for a

thousand years, if the elements do not destroy the stone; as the pyramids of Egypt and the columns of Greece appear as strong to-day as they were when they were erected. They are living witnesses of the strength of the materials that compose them. The endurance of iron under similar circumstances may be considered still a disputed question. If 50,000 pounds will break a bar in a test taking a limited time, 45,000 pounds may break it if applied long enough, but it may not. It is reasonably certain that there is some weight less than 50,000 pounds which it will sustain indefinitely, but it is also certain that a very much less weight than this will break it if it is repeatedly applied and removed.

Roebling, in his report on the Niagara railroad bridge* states that he found that the iron in the old Monongahela bridge, after thirty years' service was in such good condition that he used it in the new bridge. He also found that the iron in another bridge, over the Allegheny

* *Journal Franklin Institute*, 1860, Vol. LXX, p. 361.

river, was in good condition after forty-one years of service. On the other hand, iron rods used in stiffening the frames of some Ohio river steamboats have been found to break after less than ten years service, and on inspecting the broken rods they were found to be brittle and worthless throughout, although they were of excellent quality when put into the frames.

Resistance to Continued Steady Stress.—The question of the endurance of iron and other materials under steady stress is, as has been stated above, still a disputed one, and the records of experiments bearing upon the subject are somewhat conflicting. The results of the experiments of Vicat, which showed that an iron wire loaded to three fourths of its ultimate strength broke after remaining loaded for thirty-three months, seem to be at variance with the results obtained by later experimenters; which show that iron offers an *increased* resistance to steady stress with time. A full discussion of this subject would extend this

paper to an unreasonable length, but the conclusions to which the writer has come, after reviewing a vast amount of the work of recent authorities, may be briefly expressed thus:

Each material has a certain limit of strength (not the initial elastic limit, but usually beyond it) *within which limit it will endure a steady stress indefinitely; but any stress which causes it to pass this limit will, if continned long enough, cause it to rupture.* The exact limit for each material has yet to be determined by experiment, but it is probable that with glass, hard steel, cast iron, and all brittle materials, the limit is but little short of the point of rupture, and that these materials will endure indefinitely a strain which is almost sufficient to cause rupture. With materials like lead, tin, or other soft and ductile materials, it appears that the limit is reached at a stress which is only a small fraction of what they will bear in a test which lasts but a few minutes. Evidence of this has already been given in the remarks upon

the influence of time on tensile tests. In these metals, "of an inelastic, viscous character, which do not show an elevation of the elastic limit under strain, and which offer an increased resistance when the rapidity of distortion is increased," there seems to be a *flow' of particles* which almost any load will cause, and which almost any load will continue until rupture takes place. They are therefore unsafe metals to use in construction.

With metals like wrought iron and soft steel, Vicat's experiments seem to show that they also exhibit viscosity and flow, and that therefore long continued strain might cause their ultimate rupture; but later experiments, by Prof. Thurston, Commander Beardslee, U.S.N. and others, indicate that, *within certain limits*, no appreciable flow takes place (or if it does take place it soon ceases), but on the contrary that an increase rather than a diminution of strength occurs. This latter phenomenon has been named the "elevation of the elastic limit." Still later experiments by Prof. Thurston,

however, indicate that both phenomena can be shown by the same material; the elevation of the elastic limit is exhibited in the beginning of the test, or perhaps throughout the test nearly to the end; and later on, flow is exhibited, and rupture finally çan take place under a steady and not increasing, or even under a decreasing load. Much light has been thrown upon the subject of endurance of continued strain by experiments made within the last five years, but there yet remains a wide field of research.

Resistance to Repeated Stress.—It is only within the past few years that any really scientific investigation has been made of the resistance of materials to repeated steady stresses. The results of these investigations plainly show that if a piece once resists without breaking any given stress, it is by no means certain that it will resist an indefinite number of repetitions of that stress.

As the result of a long series of experiments for the Prussian government, A. Wöhler, in 1858, first pointed out that

a load much less than that necessary to cause rupture by a single application would cause rupture if repeated a sufficient number of times; and that it was not sufficient, in experiments on materials of construction, to learn only the rupturing strength for a single application of load, but that it was necessary, for a safe foundation for calculation, to experiment upon the resistance to stress frequently repeated. The results of his researches are embodied in the following general statement, which is known as Wöhler's law*:

"*Rupture may be caused, not only by a steady load which exceeds the carrying strength, but also by repeated application of stresses, none of which are equal to this carrying strength. The differences of these stresses are measures of the disturbance of continuity, in so far as by their increase the minimum stress which is still necessary for rupture diminishes.*"

Unwin states, in reference to Wohler's

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*Weyrauch, Strength and Determination of the Dimensions of Structures. New York, 1877.

researches, that they show that the safety of a structure, subjected to a varying amount of straining action, depends upon the *range of variation* of stress to which the structure is subjected, and on the number of repetitions of the change of load. It has hitherto been assumed that the safety depends only on the maximum intensity of the stress, but this must now be considered to be erroneous. Every machine, subjected to a constant variation of load must be designed to resist a practically infinite number of changes of load. In order that it may do so, the greatest intensity of stress must be less than that for a steady load, and less in some proportion which depends upon the amount of variation the stress undergoes in its successive changes.*

Weyrauch remarks upon Wöhler's law, that in the general form already given it is without doubt correct, and it may even be considered as a *long-known* result of experience, since we continually make unconscious use of it. "If one endeavors

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† **Unwin, Elements of Machine Design, London, 1876.**

to break a beam walled in at the end with the hand, and a single pull proves insufficient, he naturally ceases, and pulls again and again, and when this fails perchance accomplishes the fracture by bending to and fro. The force of the arm is not greater in the second case than in the first, but we do not even need so great a force. We have long known therefore that by alternate stress in opposite directions, where the differences of stress are greatest, the force necessary for rupture is less than for repeated stress in a single direction, and still less than for a single application of such a stress. . . . . There remains still much room for the further development of Wohler's law. In his experiments, the stress was repeated very rapidly; the strains however require a certain time in order to reach their full intensity; we disregard now impact proper. What influence has the rapidity of the repetition, what influence the rapidity of the increase of stress, and what the duration of the individual stresses? The ques-

tions are not as yet satisfactorily answered."

Wohler found that a bar which is alternately subjected to compression and tension will endure a much smaller number of repetitions of strain than the same bar to an equal amount of tension or compression alone. Certain bars of wrought iron and steel were equally safe to resist varying bending and tensile straining actions repeated for an indefinite time when the maximum and minimum stresses had the following values:

FOR WROUGHT IRON.

In tension only from + 18,713 to + 31 pounds per square inch.

In tension and compression alternately, from + 8317 to − 8317 pounds per square inch.

FOR CAST STEEL.

In tension only from + 34,307 to + 113,436 pounds per square inch.

In tension and compression alternately from + 12475 to − 12475 pounds per

square inch. + represents tension, and — compression.

Wohler's experiments have been completely confirmed by those of Spangenberg*. The latter states that numerous experiments confirm Wohler's second deduction, viz: "*Differences* of strains at the extremes of vibrations are a sufficient cause of rupture," and that as the strain increases the *differences* which are sufficient to cause rupture become less. Experiments showed that variations of stress between the following limits may take place with equal security:

Iron	between	+160 Ctr.†	and	−160 Ctr.	per sq. in.
	"	+300 "	"	− 0 "	
	"	+440 "	"	+240 "	

Axle Cast Steel	between	+280 Ctr.	and	—280 Ctr.	per sq. in.
	"	+480 "	"	— 0 "	
	"	+800 "	"	+350 "	

Spring steel not hardened	between	+500 Ctr.	and	0 Ctr.	per sq. in.
	"	+700 "	"	250 "	
	"	+800 "	"	400 "	
	"	+900 "	"	600 "	

* Spangenberg. The "Fatigue of Metals." Translation: Van Nostrand, New York, 1876.

† A centner=110.2 pounds Avoir. and 1 German square inch = 1.0603 English square inch.

and for shearing resistance,

Axle Cast Steel	between 220 Ctr. and—220 Ctr. " 380 " " 0 "	per sq. in.

The following is one of the tables given by Wohler showing the effect of repeated bendings in one direction:

HOMOGENEOUS IRON.

Maximum strain in ctr. per sq. in.		Number of bendings before rupture.
550		169,750
500		420,000
450		481,975
400		1,320,000
360		4,035,400
320	sound after	3,420,000
300	sound after	48,200,000

Unwin remarks: "Unfortunately, Wöhler's experiments, although extensive, do not furnish decisive rules for practical guidance. They afford an explanation of the apparently high factors of safety which in certain cases experience has shown to be necessary, but they are not complete enough to indicate precisely the factor of safety to be chosen in different cases. Nor, indeed, could rules be ob-

tained without the most careful comparison of the results of researches of the kind begun by Wöhler with the actual stresses found to be safe in practice, in a great variety of cases."

For a discussion of the researches of Wöhler and Spangenberg, the reader is referred to Weyrauch's work on "Strength and Determination of Dimensions of Structures." The same work gives formulas derived from the results of Wohler's experiments, by Gerber, Shäffer and Launhardt, for the dimensioning of structures subjected to repeated stresses and to alternation of tension and compression, but the formulas are not yet generally adopted in practice, and the accuracy of the numerical constants which enter into them is doubtful.

The present state of our knowledge upon the subject of resistance to repeated stresses is singularly defective. The Germans have been the only experimenters in this field (a limited research by Sir William Fairbairn, in England,

perhaps alone excepted) and their results, as presented to us in English translations, are so beclouded with discussions of theories that they are not appreciated by the ordinary practical reader, and they have not yet found their way into English or American text-books.

There is scarcely any subject of more importance to the engineering profession. Wohler's investigations are of immense value as far as they go, but they must be supplemented by still more extended investigations before they can be available for general practice. The field is such a large one that it would take a century for private experimenters to explore it. The research can be efficiently made only under the direction or patronage of government.

Resistance to Shock.—Materials are frequently called upon to resist sudden and violent shocks. As a shock is caused by the sudden arrest of a *moving* force or load, it cannot be measured like a steady strain in pounds; but its amount

can be expressed in units of work or energy, as foot-pounds, or the product of mass into velocity or of force into space.

The subject of resistance to shock was treated of by the writer in a note published in the *Metallurgical Review* of October, 1877.* The following extracts from that note may be quoted here:

"The resistance to shock is not merely a resistance to an external force, but to force moving through space or to a mass moving with a velocity. It is a resistance to energy, which is measured by the product of the force into the space through which it moves, or by the product of one-half the moving mass which causes the shock into the square of its velocity.

"Also, the resistance to shock is not merely a resisting force, but a resisting force moving through space; a *work* measured by the product of the mean resisting force into the space through which it acts. The space through which the resisting force acts, in tensile strain produced by shock, is the extension.

* Vol. I. p. 190.

"If rupture does not take place, equilibrium must exist between the shock-producing energy and the shock-resisting energy, or between the work of the shock and the work of the resistance. Expressed in symbols,

$$FS = \tfrac{1}{2}MV^2 = RS',$$

in which F is the force causing the shock and S the space through which the force acts, M the mass of the moving body and V its velocity, R the mean resistance, or resisting force, and S′ the space through which the resistance acts."

The product of the mean resistance of a material to steady strain into its ultimate ductility (or amount of extension or other distortion before rupture) furnishes us an approximate measure of its shock-resisting capacity. This product is termed the "resilience," * and it is expressed in foot-pounds or other similar unit. In the graphic method of recording results, heretofore described, the

* Some writers have used this term to designate elastic range, or "spring."

resilience is represented by the area of the diagram. This measure, however, is only approximate, as the time occupied in the test may have an influence upon the amount of the resilience. Soft metals, such as tin and zinc, show greater resistance to rapid than to slow strain, while their ductility under either rapid or slow strain is nearly the same. The resilience is greater therefore under rapid than under slow strain. If the time is made as short as the endurance of a shock, a small fraction of a second, the resilience may be still greater. With wrought iron and steel probably the reverse is the case, as they offer greater resistance to slow than to rapid distortion—the ductility remaining, as far as we know, nearly constant. The resilience under strain rapid enough to constitute a shock might be much less than the resilience under steady strain. This is apparently indicated by the results of experiments on iron and steel armor plate, the plate cracking or "starring" under the impact of a shot fired

with a high velocity, to a much greater degree than would happen under the impact of the same number of foot-tons produced by a greater load at a smaller velocity.

Experiments on the resistance of materials to shock are not numerous. In practice, car axles are tested by placing them on supports at the ends, and dropping a heavy weight on them in the middle. The deflection caused by the blow or by successive blows or the number of blows they will stand without breaking is taken as a measure of their shock-resisting capacity. In the steel works, specimens are frequently tested by blows from a steam hammer, applied in various ways. No experiments, it is believed, have yet been made to determine what precise relation resistance to shock bears to resistance to steady strain and to ductility. As already stated, the product of the two latter affords an approximate measure of the former, but the precise relation probably depends upon the velocity of the shock producing

force. The impact, $\frac{1}{2}MV^2$, may be a constant quantity (M and V^2 being variable, but their product constant) but the resistance to impact, RS', may possibly not be constant, R varying as some function of V.

Resistance to Repeated Shocks.—The single violent shocks treated of above usually occur only in what are called accidents, but in all constructions repeated shocks, tremors or vibrations much less than that sufficient to cause rupture are of constant occurrence; and a knowledge of the resistance of materials to these repeated shocks is a much more important matter than a knowledge of their resistance to a single heavy shock.

Wohler's and Spangenberg's experiments teach us something in regard to the effect of repeated steady strains, but there have been scarcely any experiments on the effect of repeated shocks, and nearly all our information on this subject is the result of common observation and experience. We know that in breaking a piece of cast iron if one blow of a

sledge does not accomplish the result, several will. It is well known that pieces of machinery may be in use for years subjected to light shocks repeated millions of times, and will at some time break under a lighter shock than they have repeatedly experienced. Prof. Wood states: "Oft repeated, shocks upon metals are quite certain to produce fracture sooner or later. All metals in use have their 'life.' They can sustain only a certain amount of service."

It is generally believed that repeated shocks will change the mechanical condition of a material, and render it weak; as in the case of iron, by changing the structure from fibrous to crystalline. The evidence upon this subject is, however, conflicting, and direct experiments will have to be made before it can be satisfactorily settled.

Fairbairn says: "We know that in some cases wrought iron subjected to continuous vibration assumes a crystalline structure, and that then the cohesive powers are much deteriorated; but we

are ignorant of the causes of this change." In another place he says; "I am inclined to think that we attribute too much influence to percussion and vibration, and neglect more obvious causes which are frequently in operation to produce the change." "The fact is, in my opinion, we cannot change a body composed of a fibrous texture to that of a crystalline character by a mechanical process, except only in those cases where percussion is carried to the extent of producing considerable change of temperature."

The late John A. Roebling, in his report on the Niagara Suspension Bridge, in 1860, gives as his opinion that "a molecular change, or so-called *granulation* or *crystallization*, in consequence of vibration or tension, or both combined, has in no instance been satisfactorily proved by demonstration or experiment." This seems to be in direct conflict with the testimony of most authorities, and with a great accumulation of facts learned by common observation.

Prof. Wood, in a review of this subject, remarks: "These several facts, though apparently somewhat conflicting, show quite conclusively, that some metals will crystallize under certain conditions; that under certain conditions they may be strained millions of times without being damaged, or at least without being broken; that under certain conditions strains and shocks combined may produce crystallization; that shocks when severe will weaken metals and, if they are sufficiently numerous, will produce rupture. Much evidently remains to be learned upon this subject."

As already stated, the product of tensile strength and ductility is an approximate measure of the capacity of a material to resist a single heavy shock. We know little or nothing however concerning the relation of strength and ductility to resistance to repeated shocks. It is generally believed that the material which is best able to resist a single heavy shock is also best able to resist a succession of lighter shocks; and this belief

is acted on in practice. Thus in certain kinds of machinery pieces which are subjected to innumerable vibrations or light shocks are made of the very finest and most ductile iron or of the softest steel.

Car axles, which are subjected to continuous "hammering" while in service, are made of steel which must be so soft as to resist without breaking one or more blows of a heavy weight falling a number of feet. The percentage of carbon in steel for axles is therefore kept under a certain figure in order that the steel may be soft enough to stand the test without breaking.

It is tolerably certain that the axle which will resist the test of heavy blows without breaking will also not break at the beginning of its service by an accident, such as a derailment, which causes it a very heavy shock, but will rather bend; but it is not at all certain that this axle would have a longer "life" in ordinary service than one that is less ductile, and that would be broken under the test by blows. Neither is it certain

that the very soft steel used in vibrating pieces of machinery would have as long a life as harder steel used in place of it.

The most valuable contribution to our knowledge upon the subject of the resistance of steel to repeated shocks, is that given by Mr. William Metcalf, in a letter to the *Metallurgical Review* for December, 1877. It is all the more valuable, since it is directly in opposition to the common belief mentioned above, viz: that soft steels are the best adapted to resist repeated shocks and vibrations. The importance of the subject will justify the reprinting here of a brief extract.

"This action of resistance to vibration we first observed at the Crescent Steel Works about three years ago, and it was a complete surprise to us, as up to that time we had always used the mildest steel to resist such strains.

"The piston rods of steam hammers used on steel always break. In hammers where the life of a wrought iron rod was about three months, a mild steel rod was found to last about six months. To im-

prove upon this still milder rods were tried, and four to five months' use obtained, to the surprise of everybody. An accident caused the hurried use of a rod much higher than any ever tried before, probably containing .60 carbon. Immediate provision was made for its replacement by a mild rod, its destruction being expected in a few weeks. The high rod ran over two years, or about four times as long as the average of milder rods.

"The next case was that of steel for small pitmans, where the test required was that a machine should run 4½ hours, at a rate of 1200 revolutions per minute, unloaded, before the pitman broke. These pitmans were unforged in the middle, and consisted of a piece of straight round bar with a head welded on each end, the middle of the piece being left as it came from the rolls. This explanation is necessary in order that it may be understood that no accidents of forging affected the results.

"The first trial was with .53 carbon steel: mean time of six trials, 2 hours 9⅛

minutes. Second trial, .65 carbon steel: mean time of six trials, 2 hours 57½ minutes. Third trial, .85 carbon steel: mean time of three trials, 9 hours 45 minutes, or more than double the requirements. This was satisfactory and the trials were stopped.

"These trial pitmans were all of uniform quality except as to carbon. This led to the trial of a set of twelve pitmans taken from ingots which were carefully analyzed by Prof. J. W. Langley, who published a paper on the results in the *Am. Chemist* of Nov., 1876.

"These pitmans were of a finer quality of steel than the above.

The .30 C. ran 1 h. 21 m. heated and bent before break'g.
" .49 " 1 h. 28 m. " " " "
" .53 " 4 h. 57 m. broke without heating.
" .65 " 3 h. 50 m. broke at weld where imperfect.
" .80 " 5 h. 40 m.
" .84 " 18 h.
.87 carbon broke in weld near the end.
.96 " ran 4 h. 55 m. and the machine broke down."

Should Mr. Metcalf's results be found on further experiment to hold good for all kinds of steel it may well be doubted

whether the practice of using soft steel for car axles is the best practice, and also whether engineers who have used the softest steels in bridges have used the material which offers the greatest security to human life. The increasing use of Bessemer and Siemens-Martin steels in structures and the substitution of these materials for wrought iron renders the subject one of vast importance. A thorough series of experiments on the resistance of the various steels to repeated shocks and on the relation which this resistance bears to tensile strength, ductility and other mechanical properties, and to chemical composition would be of far greater value to the world than the researches of Wöhler and Spangenberg on resistance to repeated steady loads.

It may be well to explain why a knowledge of the relation between resistance to repeated shocks and other mechanical properties is important, as well as a knowledge of the absolute value of this resistance for various materials: Direct experiments on resistance to repeated

shock will be somewhat difficult, and they may take a long time to make; while experiments on tensile, compressive or torsional strength, or on ductility may be made at most in a few hours. If then it can once be settled what relation exists between these kinds of strength and ductility and resistance to repeated shock for all materials, it may then be possible to tell with precision from the "strain diagram" furnished by a tensile or torsional test of any material what is the capacity of that material to resist repeated shocks, without subjecting it to direct experiment.

It would be eminently proper that the series of experiments mentioned above should be made either by government or under its patronage; but in view of the increasing use of Bessemer steel in construction, and the immediate necessity existing that we should know something of its ability to resist continued shocks before putting it into structures, and also of the proper kind of steel to be used under different conditions, it seems prob-

able that it would be to the interest of the Bessemer steel companies to make such experiments for their own benefit.*

Conclusion.—All the various forms of stress to which materials can be subjected have been treated of at length, but the subject is by no means exhausted. Much might be said of the effect of different conditions in increasing or decreasing strength. Of these are: influence of temperature of the metal when cast; of mass of casting; of temperature of piece when tested; of amount of work done on piece; of reheating, rerolling and welding; of annealing; of remelting; of compression while in the fluid condition; of cold-rolling; of removing the outside surface; of punching or drilling holes in plates, etc. The influences of

* The writer has recently designed an apparatus for the use of Bessemer steel works and others, for the purpose of testing the relative resistance of different grades and tempers of steel or other metals to long continued and repeated small shocks, by which a number of pieces can be tested at once, and the test of each piece made in a few minutes or in several years as desired. He hopes soon to have such an apparatus built and to publish results obtained from it.

these conditions have been discussed by several writers on strength of materials, and it is not necessary to extend this paper further by treating of them here. As a most important practical fact it may be well to state that the process of compressing metal while in the liquid condition has been found to cause a great increase in strength, and it is likely that it will be extensively adopted in the manufacture of steel. The process of cold-rolling has been found to increase the strength of bar iron in some cases as much as 100 per cent.

A table of the strength of various materials might be appended, but such tables already exist in abundance, and the writer would rather discourage, than otherwise, reliance on published figures of strength. In the first portion of this paper several examples were given to show the unreliability of such figures. In all important structures the material to be used should first be tested; there should be no guesswork in regard to the strength of a bridge rod or any piece on which the safety of life may depend.

If the result of these articles shall be to show to manufacturers and users of materials how recklessly and incorrectly tests of these materials have been and are being made, if they shall tend in any degree to bring about some reform in the common method of testing, and if they shall help make more general the belief that no material should be used in an important structure until specimens of it are first subjected to test, their object will be accomplished.